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THREE-DIMENSIONAL TRAJECTORY ANALYSIS FOR ROUND-TRIP MISSIONS TO MARS

By Gerald Knip, Jr., and Charles L. Zola

Lewis Research Center
Cleveland, Ohio

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SUMMARY

For orbit-to-orbit round-trip missions to Mars, the dependence of mission velocity-increment requirements on mission time, wait time, atmospheric braking, and synodic period of departure was investigated. The analysis is characterized by noncoplanar, elliptical planetary orbits; successive two-body approximations; and impulsive velocity increments. Round trips from 150 to 1000 days and wait times from 0 to 500 days were studied for departure dates in 1970-71 and 1979-80.

The velocity-increment requirements for each round trip were based on three modes of operation: (1) atmospheric braking on arrival at Mars and Earth, (2) atmospheric braking on arrival at Earth, and (3) all propulsive braking. All three velocity-increment summations were minimized for each mission time.

The dependence of velocity-increment requirements on mission time was such that a number of local minimum velocity-increment requirements occurred for mission times between 150 and 1000 days. One of these minimums was for a mission time of about 475 days and a wait time of 40 days. Another, lower, minimum occurred for a mission time of about 950 days and a wait time between about 310 and 450 days. The exact wait time was dependent on the synodic period of departure. With atmospheric braking, the difference between these minimum values decreased. This trend may be significant in deciding between a long and a short round-trip mission to Mars.

For missions between 225 and 600 days, increasing the wait time shifted the velocity-increment-requirement curve to longer mission times and higher velocity increments. For mission times between 640 and 1000 days, however, increasing the wait time, in general, shifted the velocity-increment curve to longer mission times but lower velocity-increment requirements.

For all except the most preliminary mission studies, utilization of trajectory data that incorporate the effects of the ellipticity and inclination of Mars' orbit was desirable.

INTRODUCTION

Of fundamental importance in the planning of any space mission is a study of the trajectory requirements. These studies emphasize the interrelation of such parameters as mission time, wait time, atmospheric braking, synodic period of departure, and velocity-increment requirements.

Most previous round-trip interplanetary trajectory studies (e.g., refs. 1 to 3) have been based on a circular coplanar model of the planetary orbits. Because planetary orbital eccentricity and inclination are neglected in these studies, all values of trajectory variables are approximate. Reference 4 includes three-dimensional (characterized by mutually inclined, elliptical planetary orbits) effects for some arbitrary "nonstop" (zero wait time) round trips to Mars. A three-dimensional trajectory analysis for round-trip missions to Venus is presented in reference 5.

Three-dimensional trajectory data that will be useful in planning round-trip missions to Mars are presented herein. Since these data were calculated by the procedure of reference 6 (characterized by noncoplanar, elliptical planetary orbits; successive two-body calculations; and impulsive velocity increments), they are approximate. The data are, however, significantly better than those obtained with circular coplanar orbits (refs. 1 to 3). Compared with "exact" n-body calculations, velocity increments obtained with the present procedure agree within 3 percent, while circular coplanar velocity increments may be in error by as much as 30 percent.

Round-trip mission times from 150 to 1000 days and wait times in the range from 0 to 500 days were studied for departure dates in 1970-71 and in 1979-80. These two periods represent approximately the extremes in distance between Earth and Mars at the time of opposition (time at which the heliocentric longitudes of Earth and Mars are equal). All trips start and end in circular orbits at 1.1 planet radii. Propulsive velocity-increment data for round trips employing three operational modes are presented. These modes are (1) atmospheric braking on arrival at both Mars and Earth, (2) atmospheric braking on arrival at Earth, and (3) all propulsive braking.

A comparison of circular coplanar data and three-dimensional data is presented.

ANALYSIS

The calculation procedure described in reference 6 was used in determining the required trajectories for each of the round trips investigated. This procedure is based on a three-dimensional model of the solar system that has mutually inclined, elliptical planetary orbits, successive two-body approximations, and impulsive velocity increments. A typical trajectory that is composed of three conic sections (escape hyperbola, heliocentric conic, and encounter hyperbola) starts and ends at the perigees of the respective hyperbolas.

For any round-trip mission, items such as communication distance, radiation shielding, sustenance weight, and reentry velocity all influence the choice of an optimum trip. Thus velocity increment is only one factor, albeit a major one since the propellant is the heaviest constituent of the vehicle. The trajectory of prime interest therefore is that one requiring the minimum velocity increment for any given mission and wait time. The four velocity increments required for the orbit-to-orbit round trips considered herein are:

(1) To depart a circular parking orbit at 1.1 Earth radii, ΔV_1

(2) To establish a circular parking orbit at 1.1 Mars radii for use during a given wait time, ΔV_2

(3) To depart the circular parking orbit at Mars, ΔV_3

(4) To establish a circular parking orbit at 1.1 Earth radii, ΔV_4

These velocity increments are all assumed to be applied impulsively.

To determine the minimum propulsive velocity increment for a given value of mission time and wait time, a range of Earth-to-Mars trip times was investigated for a range of departure dates. The results of reference 2 were used in selecting these initial ranges. After the values of $\Delta V_1 + \Delta V_2$ were obtained from curves of the form shown in figure 1(a), the required Mars-to-Earth trip times and the return departure dates were calculated from the following expressions:

$$T_{♂⊕} = T_m - T_{⊕♂} - T_w \tag{1}$$

$$D_{♂} = D_{⊕} + T_{⊕♂} + T_w \tag{2}$$

(All symbols are defined in the appendix.) Values of $\Delta V_3 + \Delta V_4$ were then obtained from curves of the form shown in figure 1(b). Combining the data of figures 1(a) and (b) gave the total propulsive velocity increment required for the mission as a function of departure date from

Earth. These data are presented in curves of the form shown in figure 1(c). From the envelope curve of figure 1(c), a minimum value of the total propulsive velocity increment $\sum_{i=1}^{4} \Delta V_i$ required for the given mission time and wait time can be obtained.

One possible means of reducing the propulsion requirements is to employ atmospheric braking either on arrival at Earth or on arrival at both Mars and Earth. The previous procedure was therefore again applied to minimize $\sum_{i=1}^{3} \Delta V_i$ for the case of atmospheric braking on arrival at Earth and $\Delta V_1 + \Delta V_3$ for the case of atmospheric braking on arrival at Mars and Earth.

RESULTS AND DISCUSSION

Ranges of round-trip mission time, wait time, and departure date were investigated for round trips between Earth and Mars. Mission times between 150 and 1000 days were investigated for departure dates in 1970-71 and in 1979-80. Wait times investigated were in the range from 0 to 500 days.

Velocity-Increment Requirements

For each mission time and wait time investigated, three types of round trip are presented. The three types are characterized by atmospheric braking at Mars and Earth, atmospheric braking at Earth, and all propulsive braking (parts (a), (b), and (c), respectively, figs. 2 to 50). For each type trip, the total velocity-increment requirement has been minimized.

Departure dates in 1970-71. - Listed in the following table together with the mission times and the corresponding figures are the wait times investigated for round-trip missions departing for Mars in 1970-71:

Wait time, days	Mission time, days	Figure
40	150, 200, 250, 300, 420 500, 600, 700, 800, 900	2, 3, 4, 5, 6 7, 8, 9, 10, 11
310	800, 900, 1000	12, 13, 14
450	800, 900, 1000	15, 16, 17

Departure dates in 1979-80. - Wait times investigated for round-trip missions with departure dates in 1979-80 are listed in the following table:

Wait time, days	Mission time, days	Figure
0	640, 700, 800	18, 19, 20
40	150, 200, 300, 420, 500 600, 640, 700, 800, 900	21, 22, 23, 24, 25 26, 27, 28, 29, 30
100	400, 420, 500, 540 700, 800, 860	31, 32, 33, 34 35, 36, 37
200	700, 800, 850	38, 39, 40
310	800, 900, 950, 1000	41, 42, 43, 44
450	800, 900, 1000	45, 46, 47
500	900, 950, 1000	48, 49, 50

In each figure, a velocity-increment parameter is plotted against departure date for several trip times from Earth to Mars. The time of day for all departure dates is zero hours universal time (mean solar time of the meridian of Greenwich, reckoned from midnight). For a given value of mission time and a specific type of round trip, the minimum value of total propulsive velocity increment can be determined from each figure. For example, figure 2(a) indicates the velocity-increment requirements for a 150-day mission in 1971 employing atmospheric braking at Mars and Earth. A minimum total propulsive velocity increment of about 15.34 miles per second results for a departure date of May 2, 1971 and an Earth-to-Mars trip time of 60 days.

The corresponding values of departure date and Earth-to-Mars trip time along with equations (1) and (2) permit reading the individual velocity increments (for T_m = 150 to 600 days with T_w = 40 days and T_m = 800, 900, 1000 days with T_w = 450 days) from figures 51 and 52. Figure 51 indicates the individual velocity increments (ΔV_1, ΔV_2, ΔV_3, ΔV_4) required for round-trip missions departing Earth in 1971. In parts (a) and (b) of the figures, ΔV_1 and ΔV_2, respectively, are given for a range of Earth-to-Mars trip times and departure dates from Earth. Values of ΔV_3 are given in parts (c) and (d), and parts (e) and (f) indicate required values of ΔV_4 for a range of Mars-to-Earth trip time and of departure date from Mars. Similarly, figure 52 indicates the individual velocity increments required for round-trip missions (T_m = 150 to 600 days with T_w = 40 days and T_m = 800, 900, 1000 days with T_w = 450 days) with departure dates in 1979 and 1980. Thus,

for the 150-day trip with an Earth-to-Mars trip time of 60 days and departing on May 2, 1971, ΔV_1 (6.96 miles/sec) and ΔV_3 (8.38 miles/sec) can be obtained from figures 51(a) and (c), respectively.

When a circular coplanar model of the planetary orbits is considered (refs. 1 to 3), the round-trip mission resulting in the lowest velocity-increment requirement is composed of two Hohmann type transfers (each having a heliocentric travel angle θ of 180°). For the three-dimensional case, however, regions of high velocity-increment requirements occur when either the Earth-to-Mars or Mars-to-Earth leg of a round trip requires a heliocentric travel angle near 180° (ref. 6). As the travel angle approaches 180°, the inclination of the transfer plane increases rapidly. As the transfer-plane inclination increases, the velocity-increment requirements also increase. When the angle between Earth and Mars measured in the plane of the ecliptic is 180°, a maximum value of velocity increment occurs, because an inclination of 90° is required of the transfer plane. The heliocentric travel angle in this case would be $180^{\circ} \pm \lambda_{♂}$ (latitude of Mars with respect to the ecliptic plane). This angle occurs, for example, on the return trip of a 300-day mission (fig. 5) with an Earth-to-Mars trip time of 100 days and a Mars-to-Earth trip time of 160 days (figs. 51(c) and (d)). The curves on the left side of figures 5 and 51(c) and (d) are for travel angles less than 180° on the return trip, while those on the right are for travel angles greater than 180°. Travel angles of 180° are also encountered on the return trip of 300-day missions with Earth-to-Mars trip times of 60, 80, 120, and 140 days. A means of bypassing this difficulty of a single-plane transfer is to use a two-plane transfer. This transfer will not produce a minimum total velocity increment for the particular mission time (ref. 6) but may be of use if launching is required during this period.

From figures 1 to 49, the minimum velocity increment for each mission time (150 to 1000 days) and wait time (0, 40, 100, 200, 310, 450, and 500 days) can be obtained for each of the three types of round trip. These minimum values of total propulsive velocity-increment requirement are shown by the three envelope curves of figures 53 and 54 for departure dates in 1970-71 and in 1979-80, respectively. For a given wait time, the total propulsive velocity-increment requirements do not decrease continuously as mission time is increased. Instead as the mission time increases from 150 to about 600 days, the propulsive velocity-increment requirements first decrease and then increase. This pattern repeats as the mission time is again increased from about 640 to 1000 days. For the range of mission and wait times investigated, a mission time of about 950 days with a wait time between 310 and 450 days (the time varies with the synodic period of departure, cf. figs. 53 and 54) resulted in the lowest propulsive velocity-increment requirements for each of the three types of round trip.

Effect of Wait Time

Since the effects of wait time on round-trip missions in 1970-71 and 1979-80 were similar, only the 1979-80 data (fig. 54) will be discussed.

For round-trip missions between 225 and 600 days (fig. 54) increasing the wait time shifts the total propulsive velocity-increment envelope curves for the three types of mission toward longer mission times and higher total propulsive velocity increments. For a wait time of 40 days, a minimum all-propulsive velocity increment of 16 miles per second (fig. 54(c)) results for a mission time of 500 days. The minimum all-propulsive velocity increment and the mission time increase to 17.5 miles per second and 525 days, respectively, as the wait time is increased to 100 days.

For round trips between about 640 and 1000 days, a different trend among wait time, mission time, and velocity increment exists. Since similar results were obtained for the three types of trip, only the all-propulsive case will be discussed. For mission times within this span (640 to 1000 days) a wait time of 0 day results in minimum total propulsive velocity increments for mission times up to about 800 days (fig. 54). For mission times between 800 and 1000 days, wait times between 100 and about 370 days resulted in minimum total velocity increments. A wait time of about 370 days for a 900-day mission results in the minimum all-propulsive velocity increment (fig. 55). Increasing the wait time from 370 to 450 days increases only slightly the total propulsive velocity-increment requirements. This effect changes with synodic period (cf. figs. 53 and 54). For the 1979-80 synodic period, a wait time of 40 days never resulted in a total propulsive velocity increment lower than could be obtained with another wait time. In general, however, for round-trip missions between 640 and 1000 days in 1979-80, increasing the wait time from 0 to 370 days shifts the total propulsive velocity-increment envelope curves (fig. 54) for the three types of mission toward longer mission times but lower total propulsive velocity increments.

Effect of Atmospheric Braking

The three modes of operation, all propulsive braking, atmospheric braking at Earth, and atmospheric braking at Earth and Mars, and their effects on velocity-increment requirements and mission time are indicated by figure 56. Shown are the minimum total propulsive velocity increments for missions with wait times in orbit at Mars of 40 and 450 days. These wait times were chosen arbitrarily. A wait time of 40 days is used until the longer mission time is encountered and increasing the wait time to 450 days becomes advantageous. The mission time at which

this increase occurs for a given type trip departing in 1970-71 is equal to or within 10 days of the mission time required for departure in 1979-80.

As shown in figure 56, atmospheric braking reduces the velocity increment required for a given mission. For example, a 950-day mission in 1971 requires an all-propulsive velocity increment of 7.6 miles per second (fig. 56(a)). Using atmospheric braking at Earth, however, reduces the velocity increment 2.3 miles per second or 30 percent.

Shortening the mission time to 460 days, increases both all-propulsive- and atmospheric-braking velocity increments. The benefit of atmospheric braking, however, is enhanced at this mission time. Although the all-propulsive velocity increment increases 4.4 miles per second, the velocity increment with atmospheric braking at Earth increases only 1.7 miles per second. Hence, the 460-day mission with atmospheric braking at Earth requires 5 miles per second, or 42 percent less velocity increment, than the all-propulsive case.

An alternate use for atmospheric braking is reducing the mission time for a given velocity increment. Thus, for an available velocity increment of 13 miles per second, atmospheric braking at Earth reduces the mission time from 382 days for the all-propulsive case to 284 days. Atmospheric braking at both Earth and Mars permits a 182-day trip.

Similar results were obtained for missions with departure dates in 1979-80 (fig. 56(b)).

Arrival Velocities

When missions utilizing atmospheric braking are planned, the velocity of arrival at the target planet must be known in order to study reentry conditions. Velocities were computed from the expression

$$V_A^2 = V_H^2 + 2\,\frac{\mu}{r} \tag{3}$$

The velocity at which the "top" of the atmosphere is first encountered is negligibly different from these values.

Figures 57 and 58 indicate arrival velocities at the planets for round-trip missions to Mars in 1970-71 and in 1979-80, respectively. Part (a) of each figure is for minimum values of $\Delta V_1 + \Delta V_3$ while part (b) is for minimum values of $\Delta V_1 + \Delta V_2 + \Delta V_3$. For mission times between 250 and 600 days, arrival velocities are shown for a wait time

at Mars of 40 days. Arrival velocities for wait times of 40 and 450 days are shown for mission times between 700 and 1000 days.

Undoubtedly a limiting approach speed exists beyond which atmospheric braking is impractical. The limiting speed would be dependent on thermodynamic considerations, human tolerance, and guidance accuracy. When the arrival velocity exceeds the limiting value, a combination of atmospheric and propulsive braking may be required. If, as in reference 7, an approach speed of 10 miles per second is possible, full atmospheric braking in place of propulsive braking on arrival at Earth would be possible for mission times between 260 and 465 days in 1970-71 (fig. 57(b)) and from 245 to over 600 days in 1979-80 (fig. 58(b)). Full atmospheric braking in place of propulsive braking at Mars and Earth would be possible in 1970-71 for mission times between 255 and 500 days. For a wait time of 40 days, however, a combination of atmospheric and propulsive braking would be required at Earth for missions of less than 700 days in 1979-80 because of arrival velocities of over 12 miles per second.

Effect of Synodic Period

Because the planetary orbits are eccentric, the synodic period of departure can have a sizable effect on the velocity-increment requirements; for example, approximately 1-mile-per-second additional increment in velocity is required for a 150-day trip to Mars in 1962 compared with 1971 (ref. 6). Because the orbit of Mars is quite eccentric (0.093), the distance of Mars from the Sun and the velocity of Mars relative to the Sun vary 26,000,000 miles and 3 miles per second, respectively. Trips to Mars should be started during a span of several months near the opposition date (date on which the heliocentric longitudes of Earth and Mars are equal). For Mars this date occurs about every 26 months or 2.17 years (synodic period). On August 6, 1971 the opposition distance is 34,600,000 miles, while on March 11, 1980 it is 61,000,000 miles. These opposition distances are approximately the extremes.

In figure 59 are plotted the minimum total propulsive velocity increments for missions to Mars with wait times of 40 and 450 days and departure dates in 1970-71 and 1979-80. For mission times between 150 and 600 days, the total propulsive velocity increments (for the three types of mission) in 1979-80 are greater than in 1970-71. As the mission time decreases, the difference increases. When atmospheric braking is employed at Mars and Earth (fig. 59(a)), the difference in propulsive velocity increment ranges from 0.6 mile per second for a 450-day trip to 14.2 miles per second for a 150-day trip.

The difference becomes even greater when propulsive braking rather than atmospheric braking is used. For example, when propulsive braking

is substituted for atmospheric braking at Mars and Earth, the difference in propulsive velocity increment for a 500-day round trip increases from 0.7 mile per second (fig. 59(a)) to 4 miles per second (fig. 59(c)).

Figure 60 indicates the orbital positions of Earth and Mars for these optimum 500-day missions. The locations of the departure and arrival points (1, 2, 3, and 4) for the 1971 trip are different from those of the 1979 trip. These differences result in variations in the departure and arrival radii, path angles, and planet velocities, which, in turn, result in the velocity-increment differences shown in figure 61. The 1971 values of ΔV_1 and ΔV_2 are higher than the 1979 values, while the reverse occurs for the ΔV_3 and ΔV_4 values.

Because of the synodic-period effect, a trajectory study for the particular synodic period of departure should be used in any detailed mission analysis.

Three-Dimensional and Circular Coplanar Comparison

A comparison is made in figure 62 between circular coplanar (ref. 2) and three-dimensional (characterized by noncoplanar, elliptical planetary orbits) minimum propulsive velocity-increment requirements for both short- and long-duration round-trip missions between Earth and Mars. For short-duration round-trip missions (300 to 600 days), errors as large as 3 miles per second in total propulsive velocity-increment requirements can result from the use of circular coplanar data. The size of the error depends on the date of departure. For long-duration round-trip missions (850 to 950 days), errors as great as 1.2 miles per second result. Thus, for all except the most preliminary Mars mission studies, utilizing trajectory data that incorporate the effects of the ellipticity and inclination of Mars' orbit is desirable.

SUMMARY OF RESULTS

The dependence of propulsive velocity-increment requirements on mission time is such that a number of local minimum values of velocity increment occurred for orbit-to-orbit round-trip missions to Mars. One of these minimums was for a mission time between 420 and 510 days and a wait time of 40 days. The exact mission time was dependent on the departure date and whether atmospheric braking was used. Another, lower minimum occurred for a mission time of about 950 days and a wait time between about 310 and 450 days. The exact wait time was dependent on the synodic period of departure. When all propulsive braking was employed, the total propulsive velocity increments at these minimums were 11.9 and 7.6 miles per second, respectively, in 1970-71. The values became 5.0 and 3.8 miles per second when atmospheric braking was

employed at both Mars and Earth. Thus, the increase in velocity increment that accompanied a reduction in trip time diminished when atmospheric braking was employed. This trend might be significant in deciding between a long and a short round-trip mission to Mars. In addition to reducing the velocity-increment requirements for a fixed mission time, atmospheric braking could be used to reduce mission time at a fixed velocity-increment requirement. For a velocity increment of 13 miles per second, atmospheric braking on arrival at Mars and Earth reduced the mission time in 1970-71 from 382 to 182 days.

The dependence of velocity increment on wait time at Mars was such that for mission times between 225 and 600 days, increasing the wait time shifted the velocity-increment curve to longer mission times and higher velocity increments. For mission times between 640 and 1000 days, increasing the wait time, in general, shifted the velocity-increment curve to longer mission times but lower velocity increments.

For preliminary planning of round-trip missions to Mars, the effect of synodic period of departure must be included. For a mission time of 500 days and a wait time of 40 days, the velocity-increment requirements with all propulsive braking were 12 miles per second in 1971 compared with 16 miles per second in 1979.

Lewis Research Center
National Aeronautics and Space Administration
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APPENDIX - SYMBOLS

D	departure date from orbit at 1.1 planet radii
P	perihelion
R_1	heliocentric radius of vehicle on date of departure from Earth, miles
R_2	heliocentric radius of vehicle on date of arrival at Mars, miles
R_3	heliocentric radius of vehicle on date of departure from Mars, miles
R_4	heliocentric radius of vehicle on date of arrival at Earth, miles
r	planet radius, miles
T_m	orbit-to-orbit round-trip mission time between Earth and Mars, days
T_w	wait time in orbit at Mars, days
$T_{\oplus♂}$	orbit-to-orbit trip time from Earth to Mars, days
$T_{♂\oplus}$	orbit-to-orbit trip time from Mars to Earth, days
V_A	arrival velocity at surface of planet, miles/sec
V_H	hyperbolic velocity of vehicle, miles/sec
$V_{\oplus 1}$	velocity of Earth on date of departure, miles/sec
$V_{♂2}$	velocity of Mars on date of arrival, miles/sec
$V_{♂3}$	velocity of Mars on date of departure, miles/sec
$V_{\oplus 4}$	velocity of Earth on date of arrival, miles/sec
ΔV_1	velocity increment to depart circular orbit at 1.1 Earth's radii, miles/sec
ΔV_2	velocity increment to establish circular orbit at 1.1 Mars' radii, miles/sec
ΔV_3	velocity increment to depart circular orbit at 1.1 Mars' radii, miles/sec
ΔV_4	velocity increment to establish circular orbit at 1.1 Earth's radii, miles/sec

α_1 heliocentric path of vehicle with respect to local horizontal on date of departure from Earth, deg

α_2 heliocentric path of vehicle with respect to local horizontal on date of arrival at Mars, deg

α_3 heliocentric path of vehicle with respect to local horizontal on date of departure from Mars, deg

α_4 heliocentric path of vehicle with respect to local horizontal on date of arrival at Earth, deg

θ transfer plane travel angle from departure radius to arrival radius, deg

λ heliocentric latitude with respect to plane of the ecliptic, deg

μ gravitational force constant of planet

Subscripts:

$\oplus$ Earth

♂ Mars

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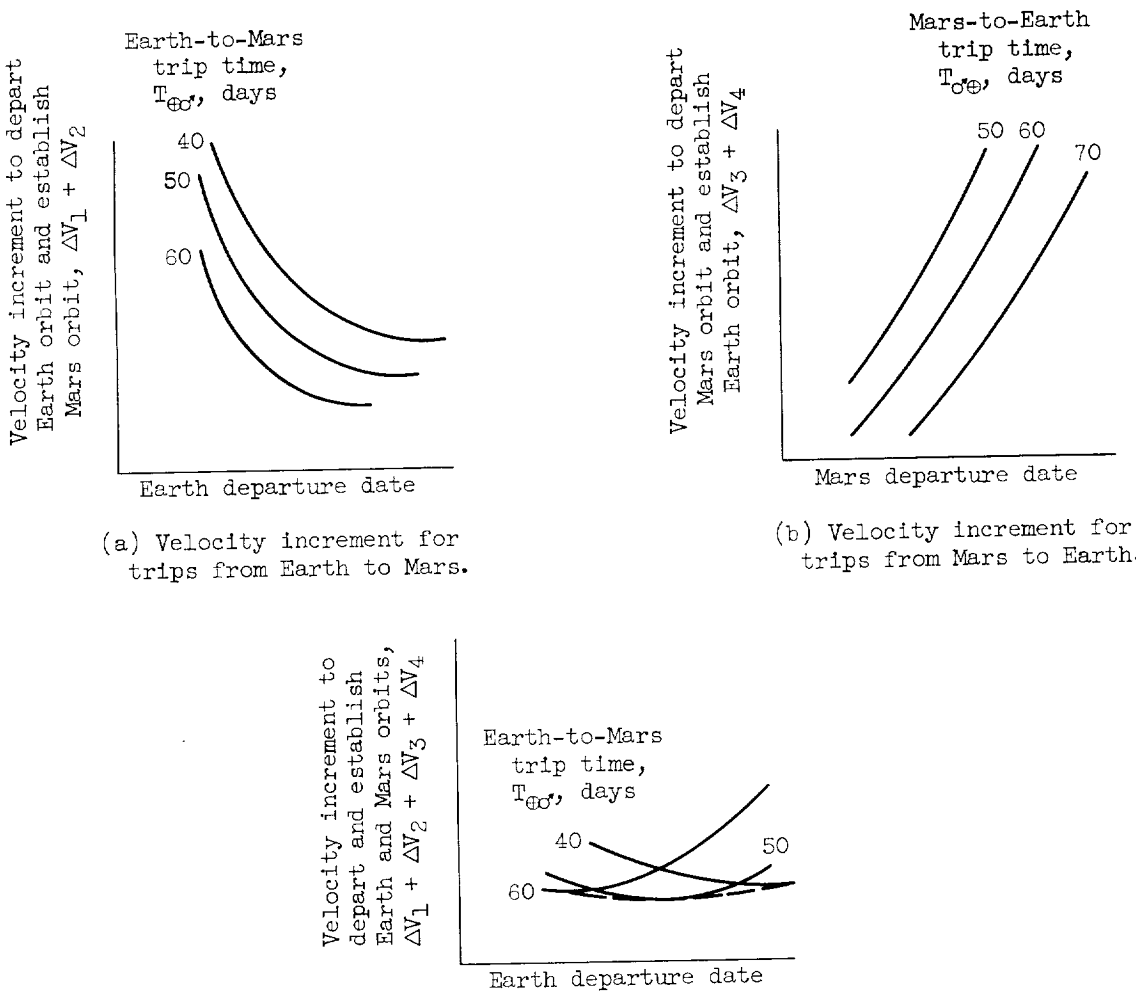
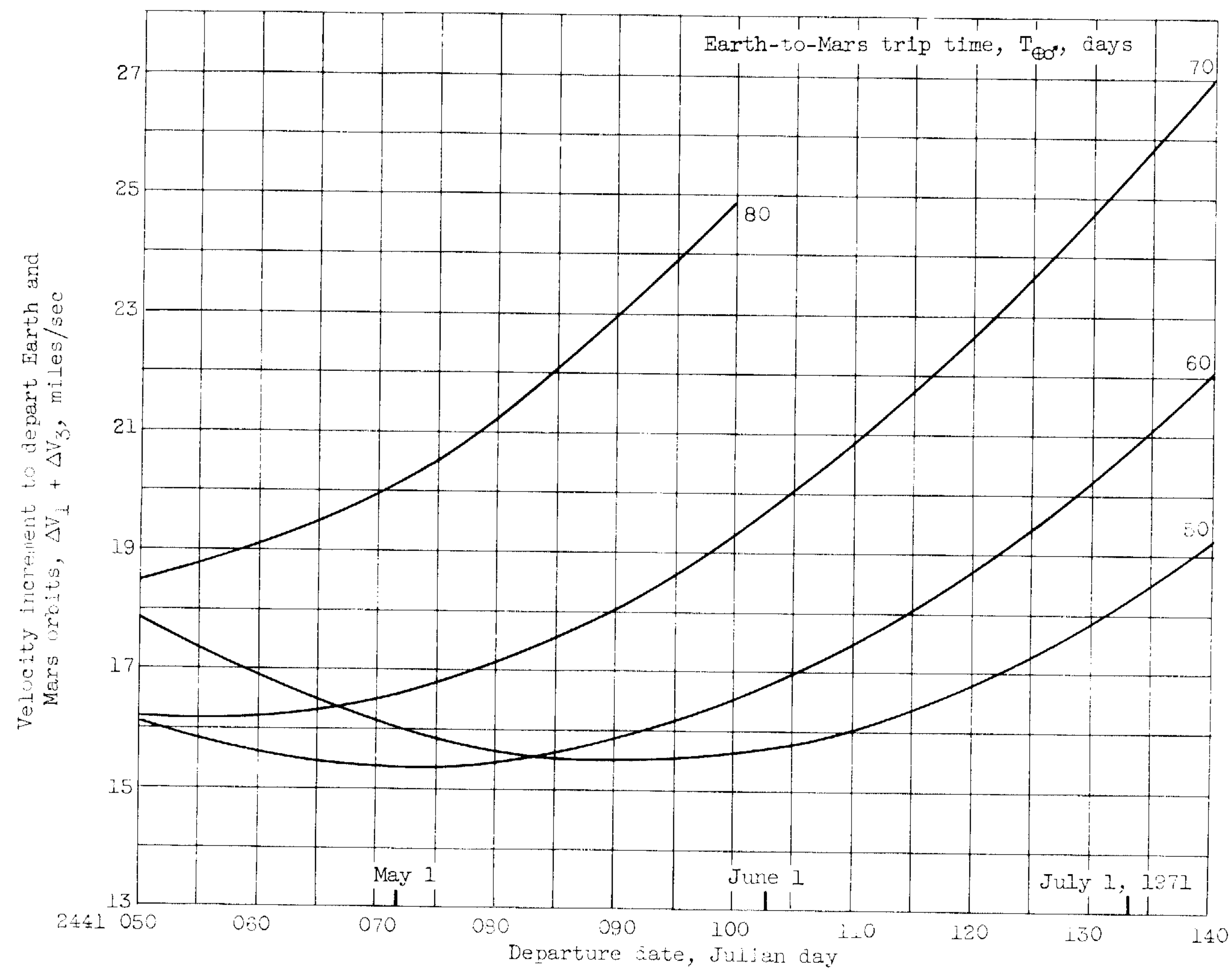


(a) Velocity increment for trips from Earth to Mars.

(b) Velocity increment for trips from Mars to Earth.

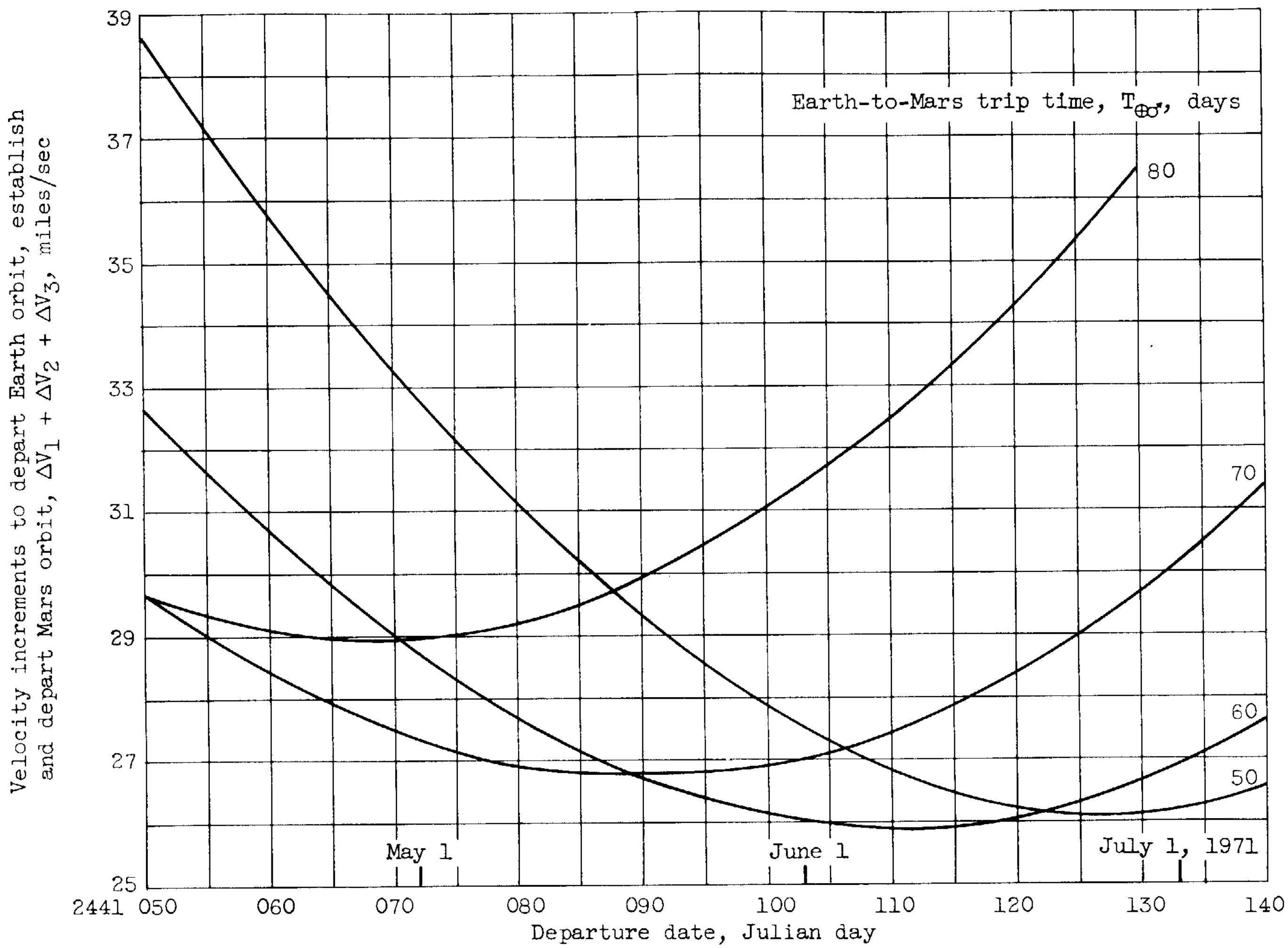
(c) Velocity increment for typical round trip. Wait time in Mars orbit, 40 days.

Figure 1. - Procedure for optimizing total velocity increment for round trip to Mars given mission time and wait time.



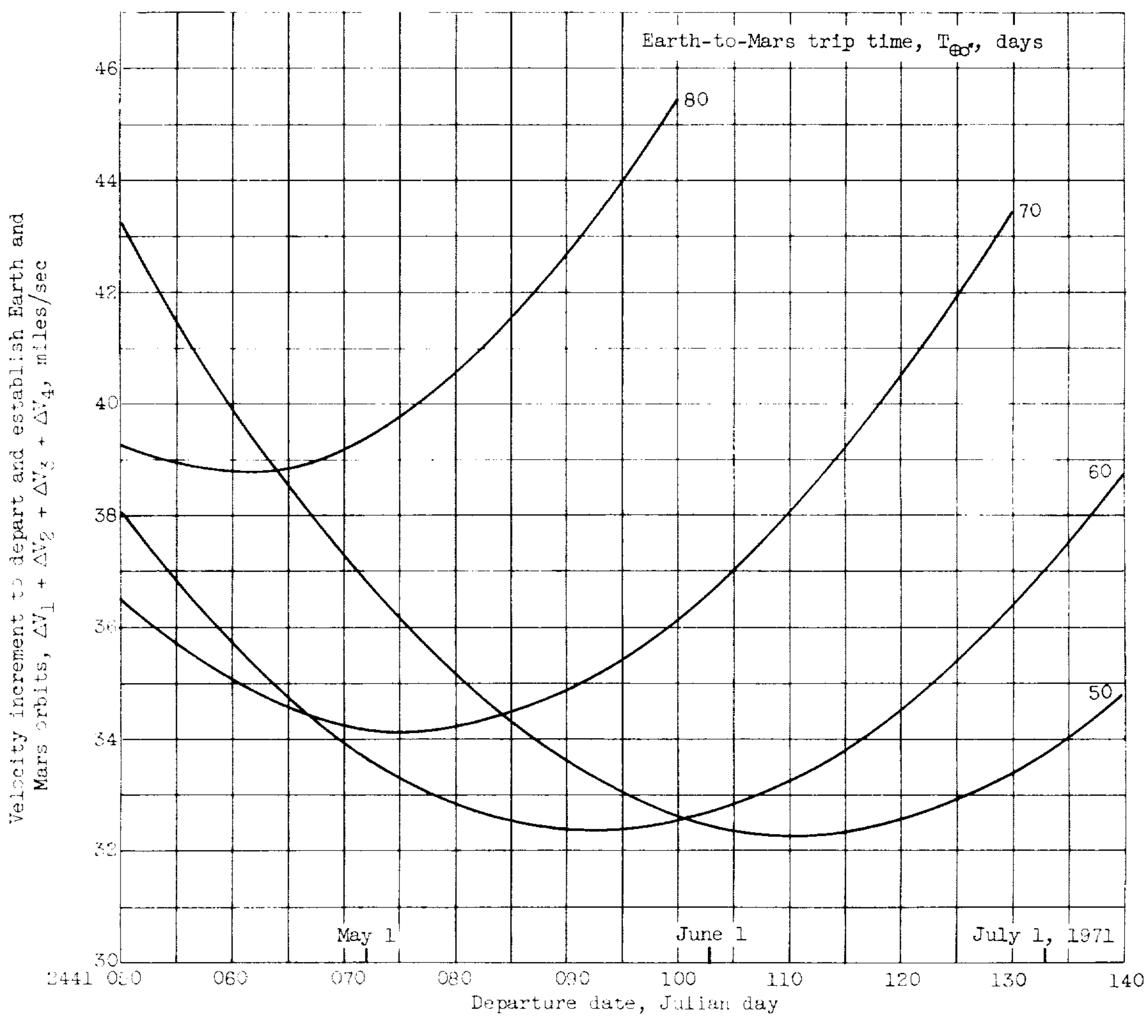
(a) Atmospheric braking at Mars and Earth.

Figure 2. - Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



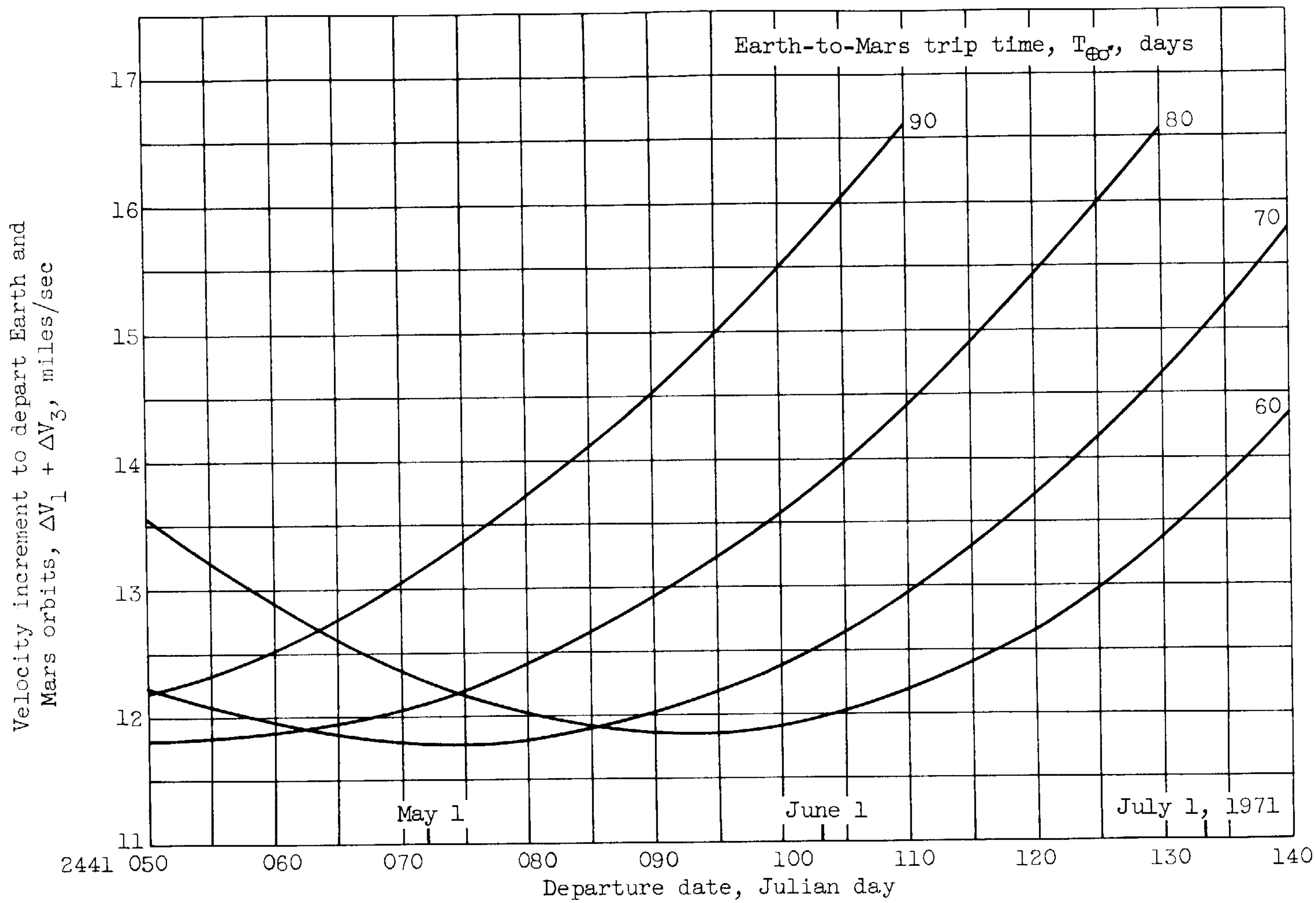
(b) Atmospheric braking at Earth.

Figure 2. - Continued. Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



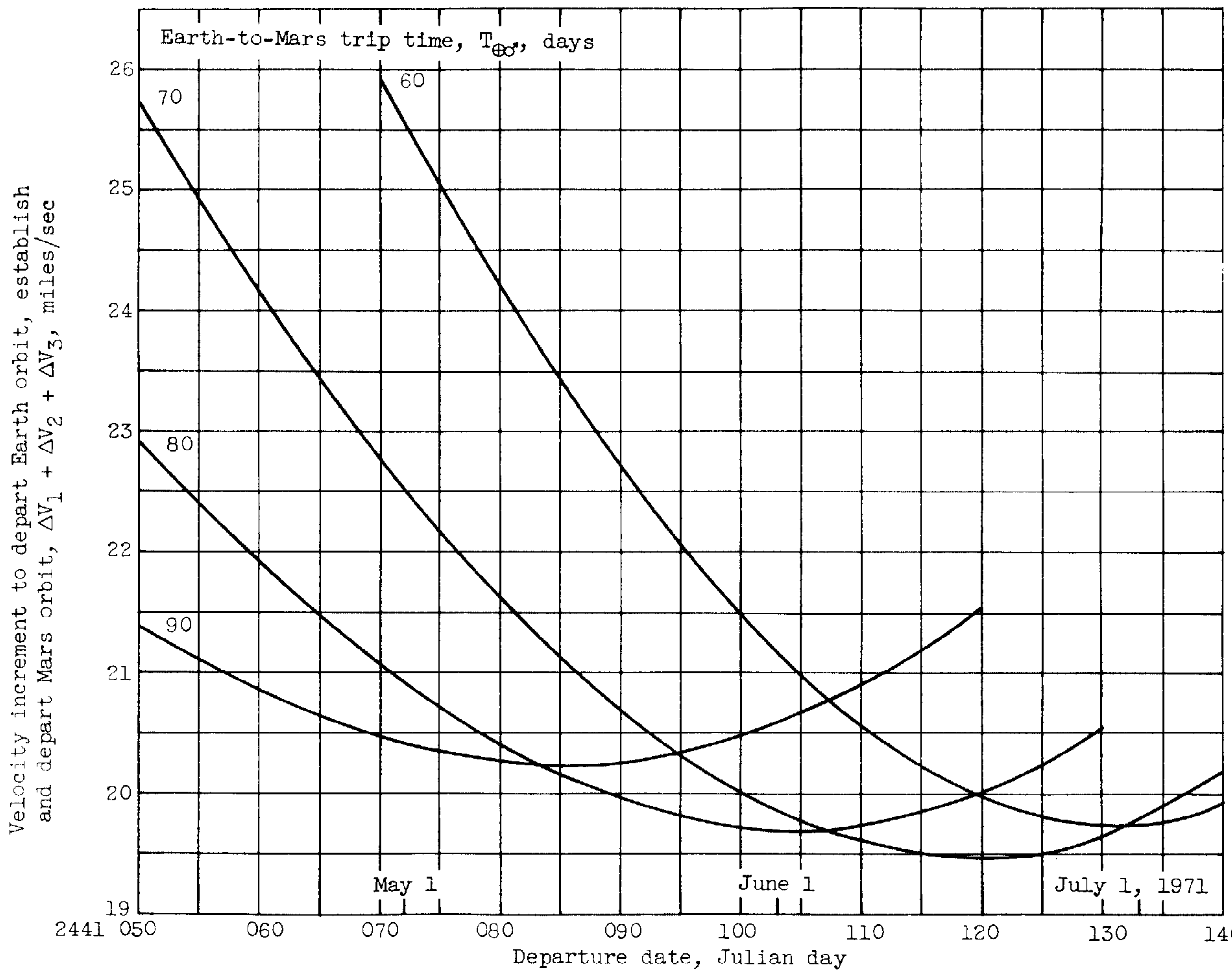
(c) All propulsive braking.

Figure 2. - Concluded. Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



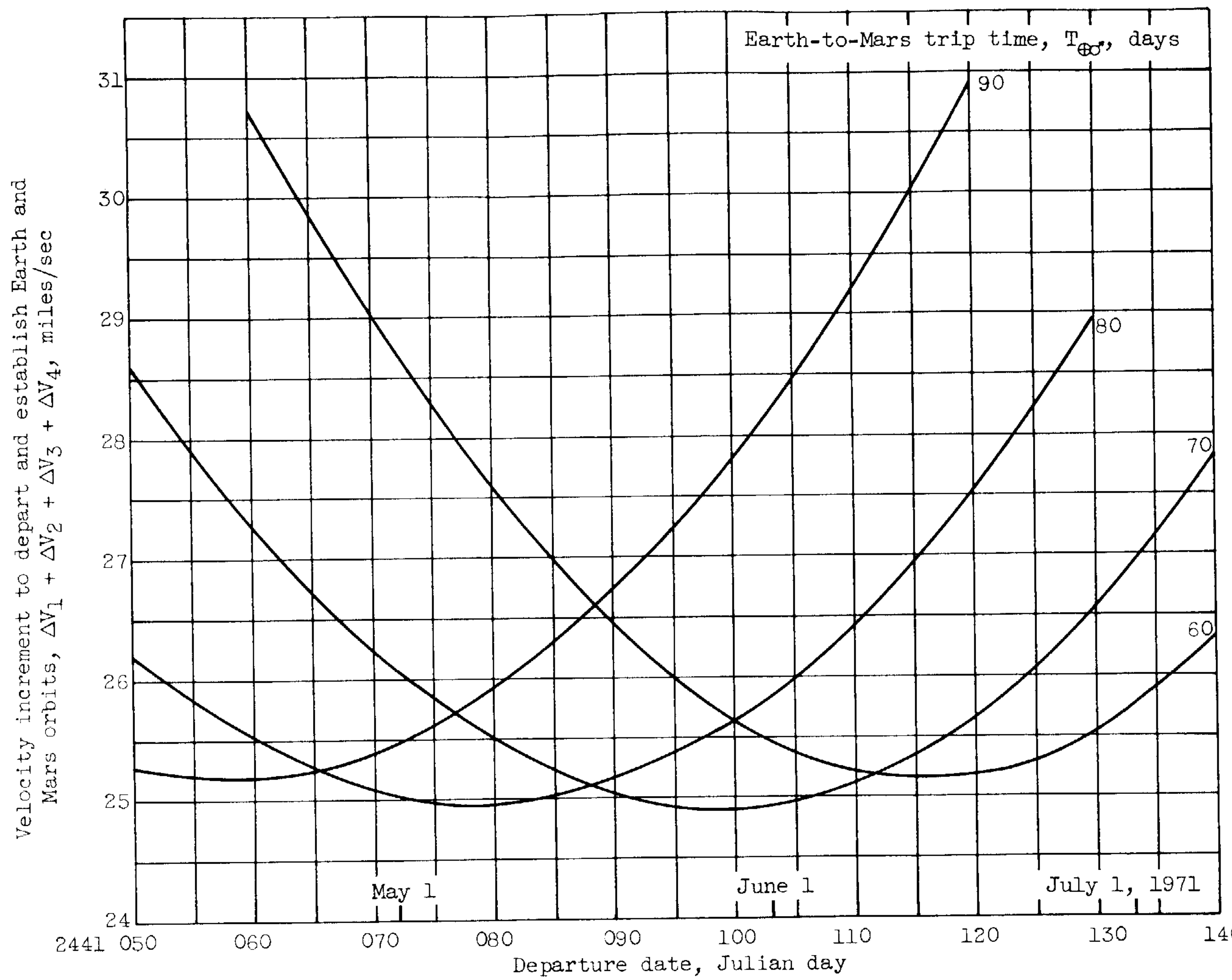
(a) Atmospheric braking at Mars and Earth.

Figure 3. - **Velocity increments for 200-day round trip to Mars.** Wait time in Mars orbit, 40 days.



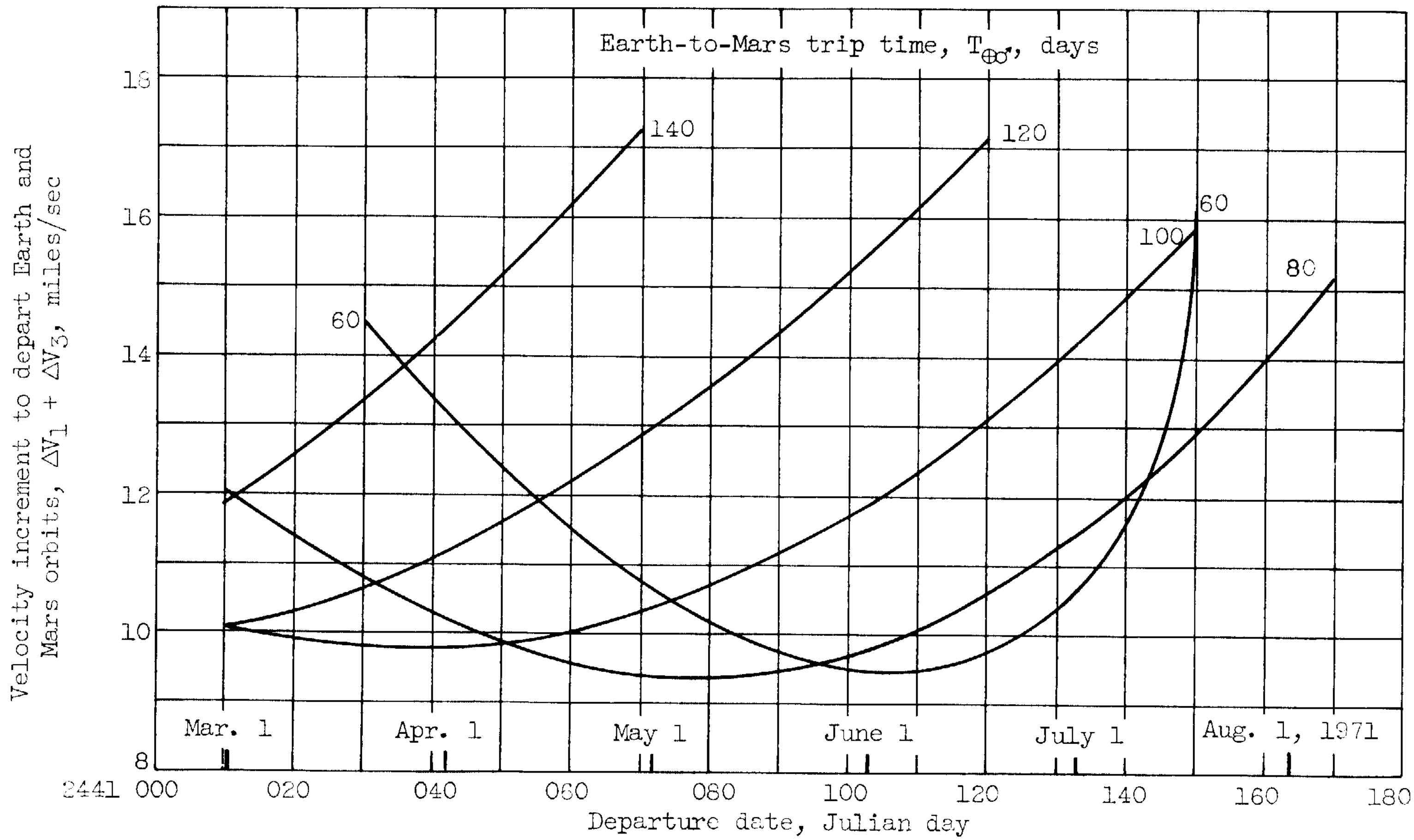
(b) Atmospheric braking at Earth.

Figure 3. - Continued. Velocity increments for 200-day round trip to Mars. Wait time in Mars orbit, 40 days.



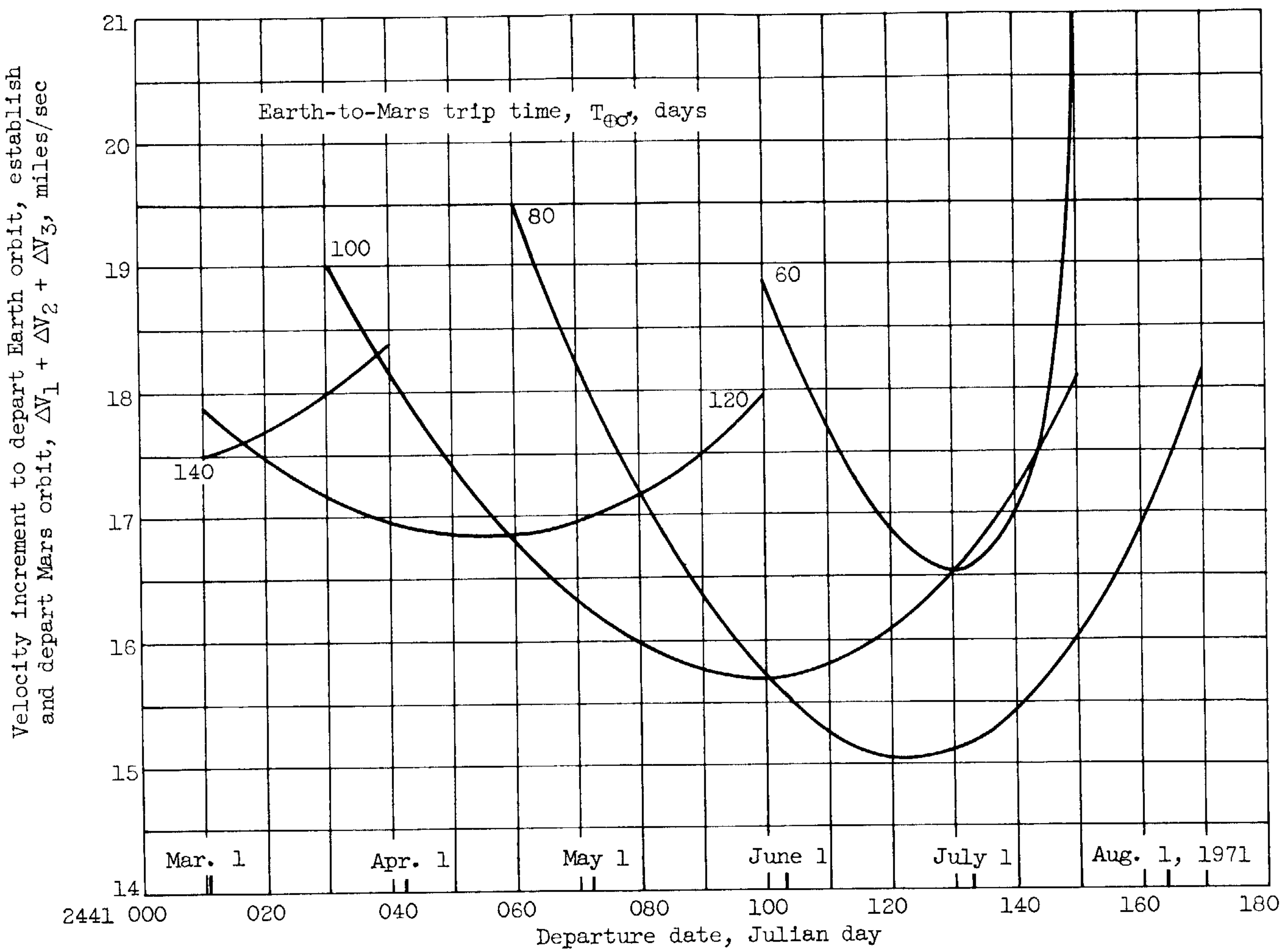
(c) All propulsive braking.

Figure 3. - Concluded. Velocity increments for 200-day round trip to Mars. Wait time in Mars orbit, 40 days.



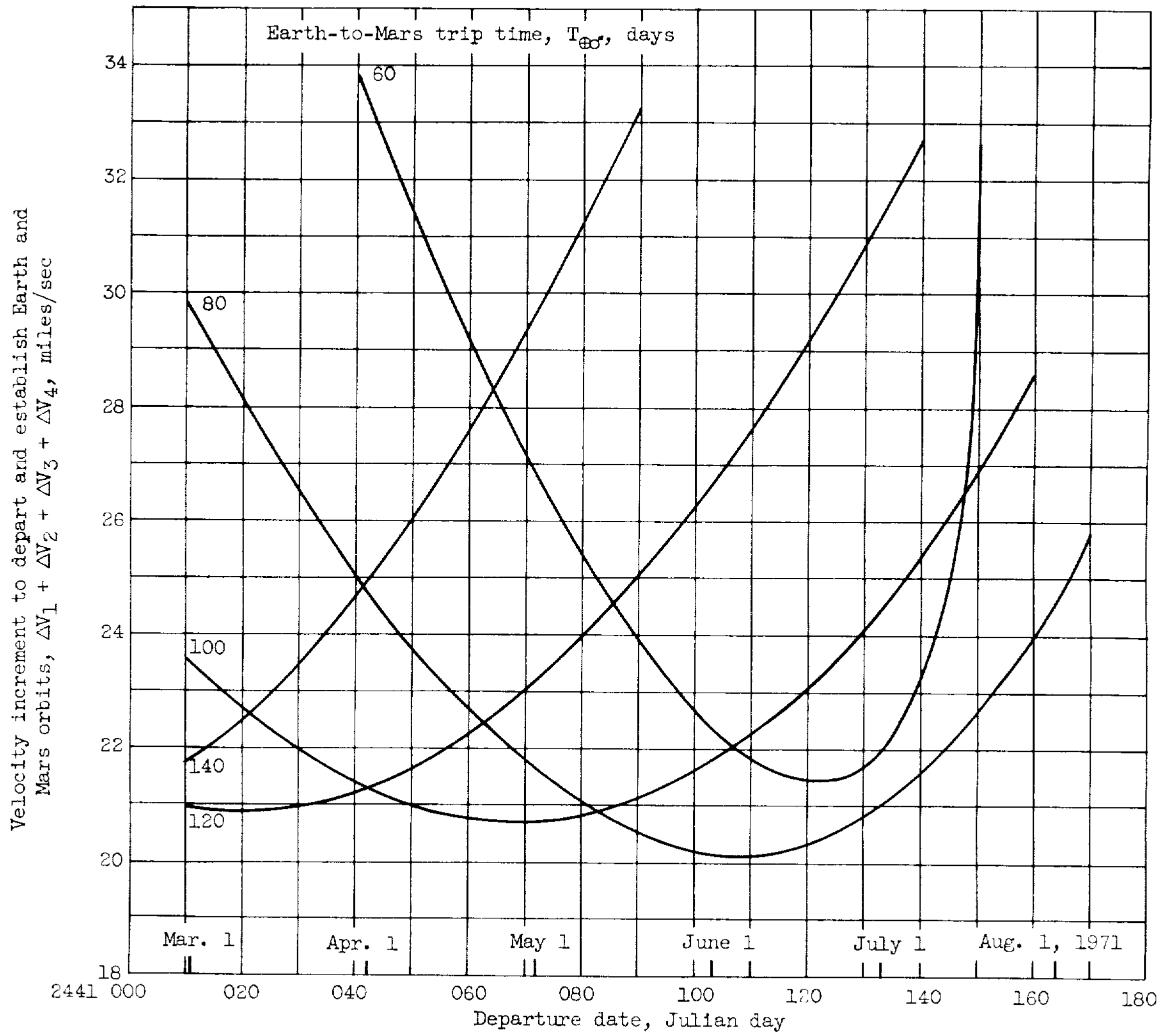
(a) Atmospheric braking at Mars and Earth.

Figure 4. - Velocity increments for 230-day round trip to Mars. Wait time in Mars orbit, 40 days.



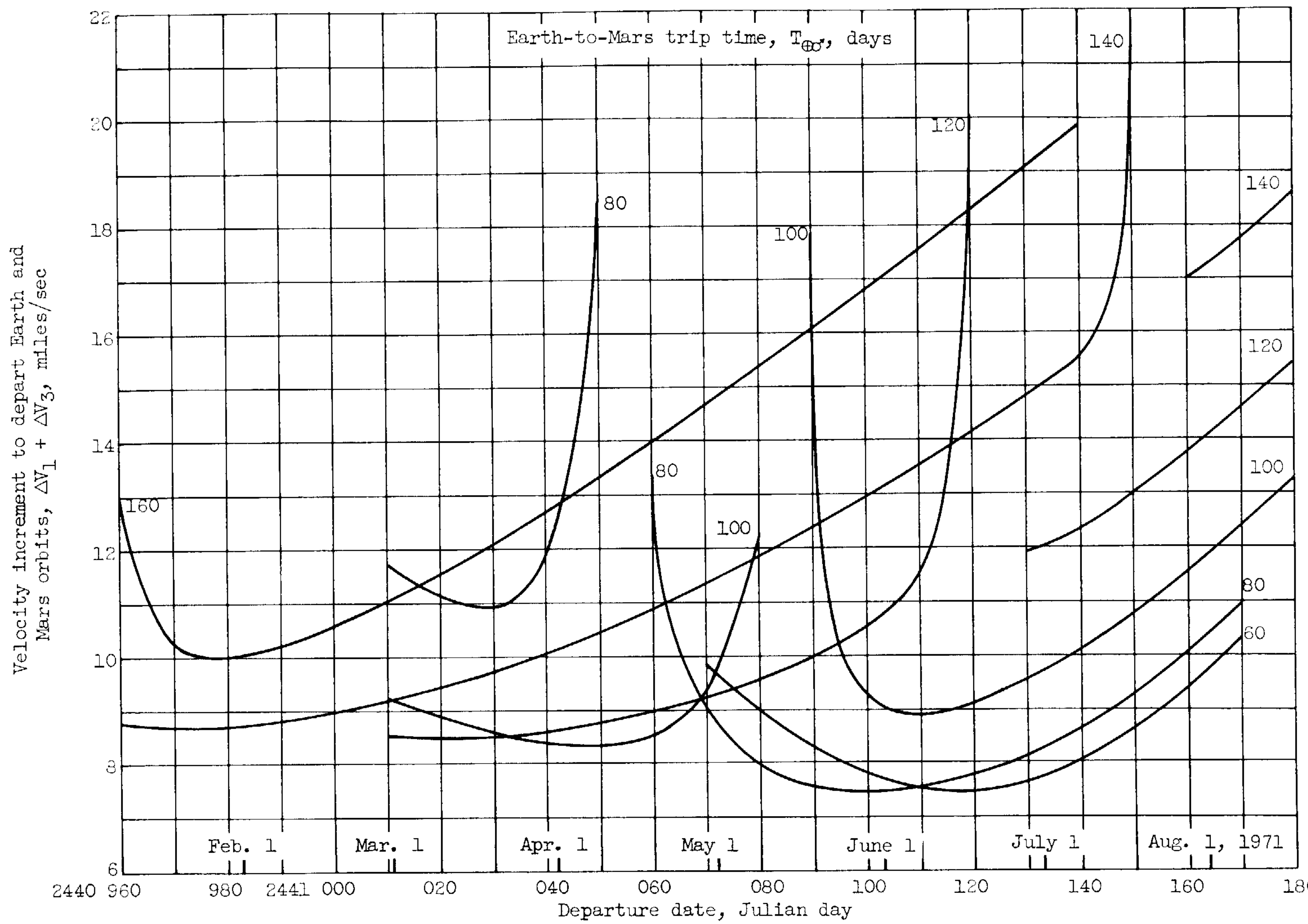
(b) Atmospheric braking at Earth.

Figure 4. - Continued. Velocity increments for 250-day round trip to Mars. Wait time in Mars orbit, 40 days.



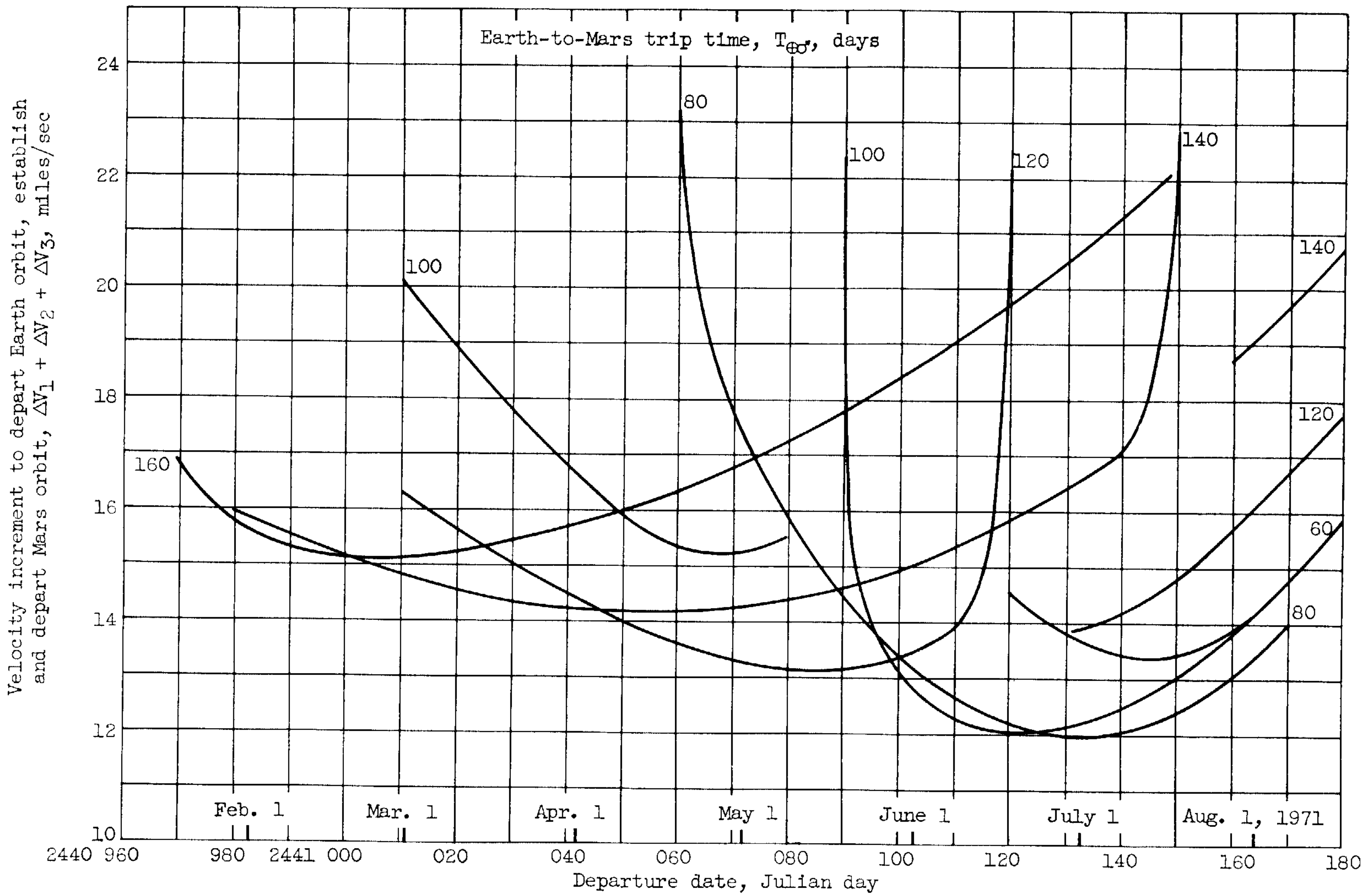
(c) All propulsive braking.

Figure 4. - Concluded. Velocity increments for 250-day round trip to Mars. Wait time in Mars orbit, 40 days.



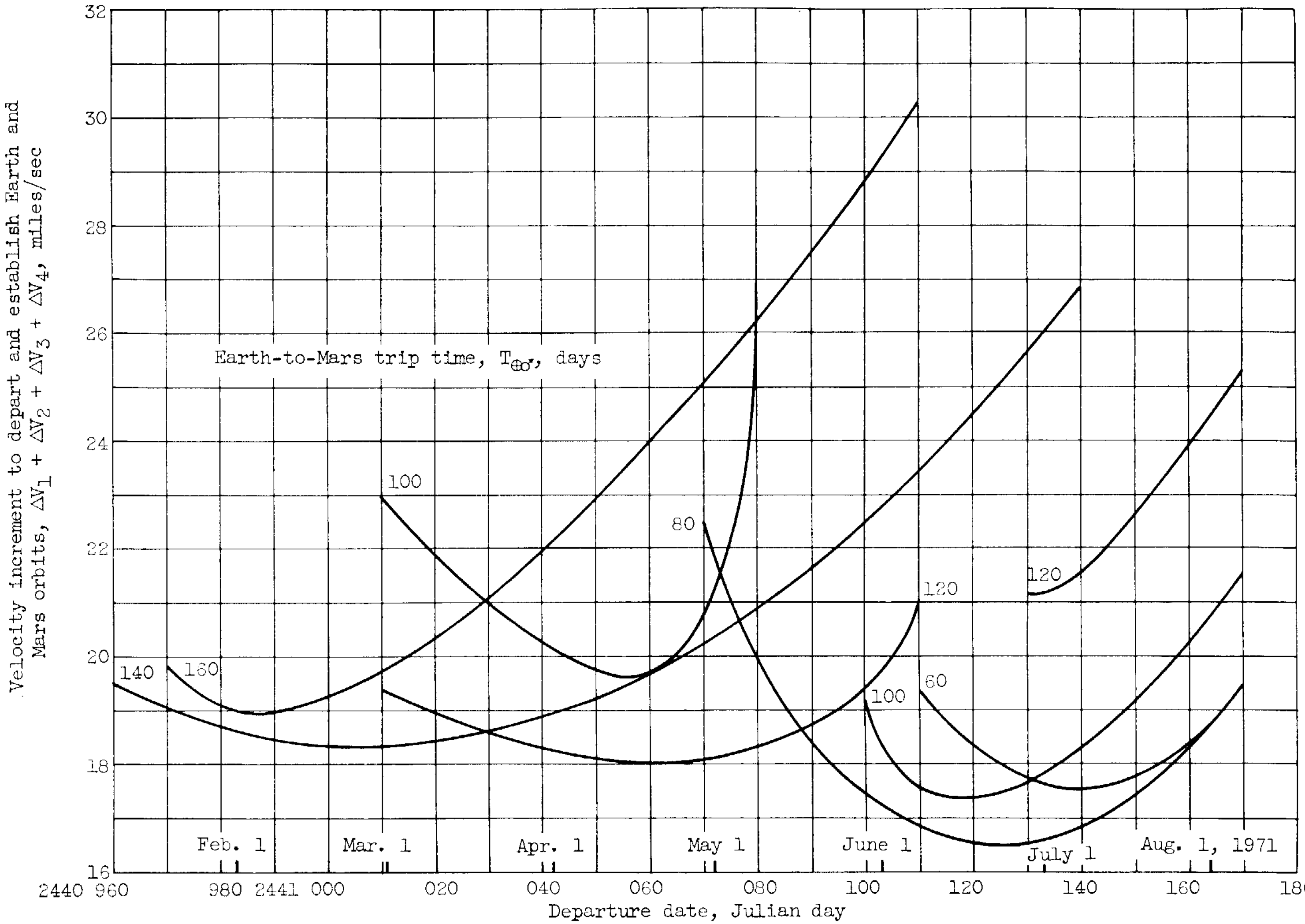
(a) Atmospheric braking at Mars and Earth.

Figure 5. - Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



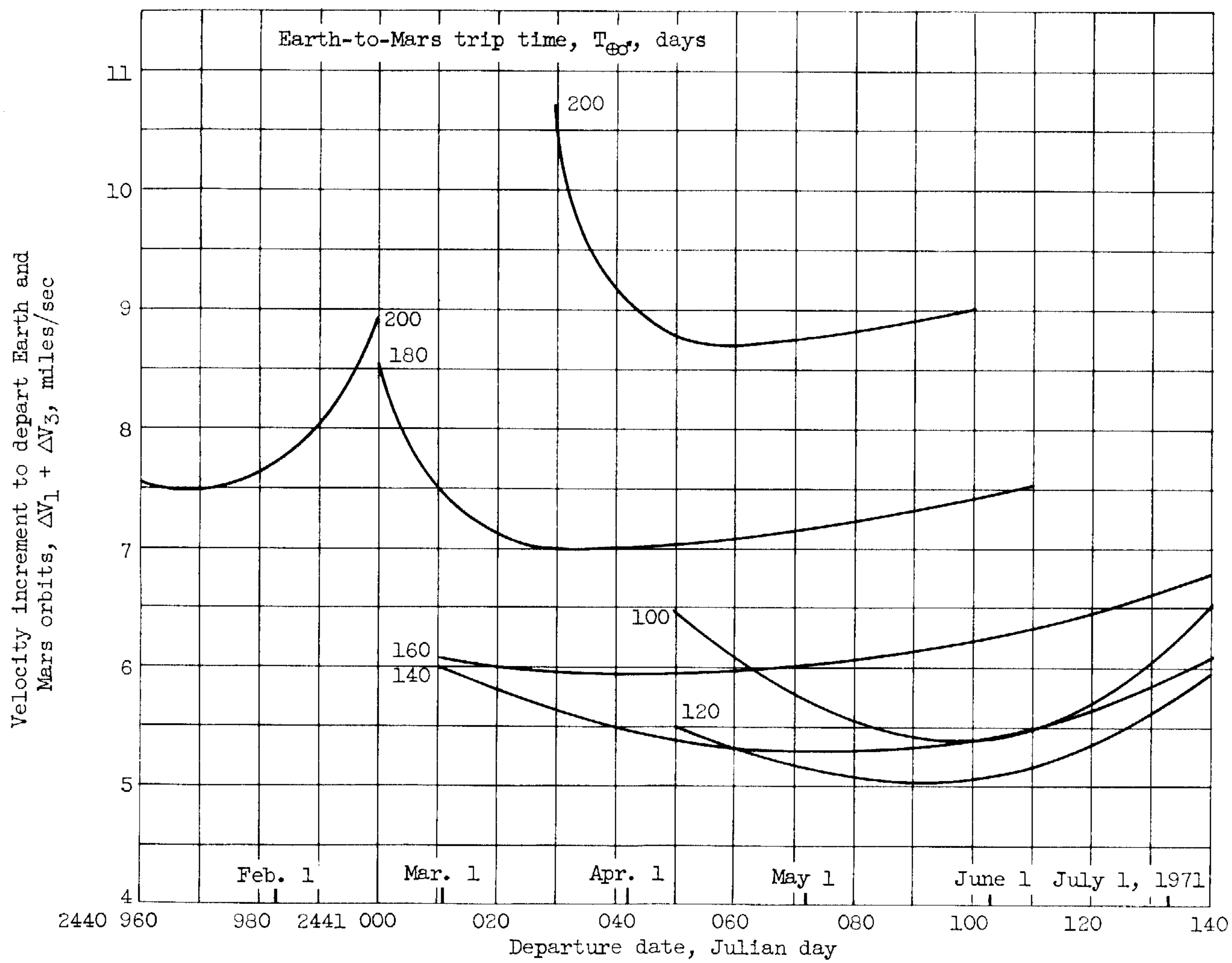
(b) Atmospheric braking at Earth.

Figure 5. - Continued. Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



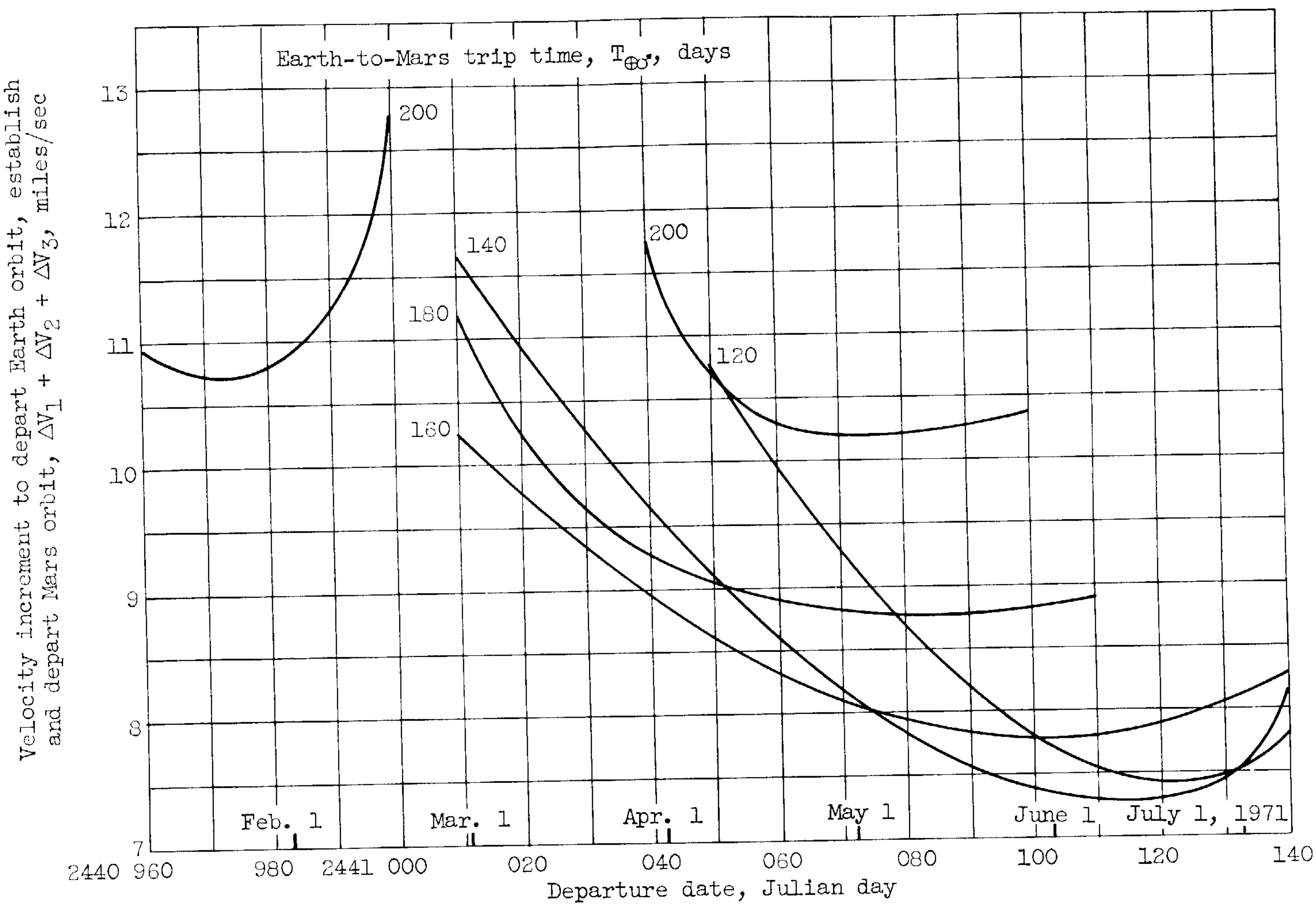
(c) All propulsive braking.

Figure 5. - Concluded. Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



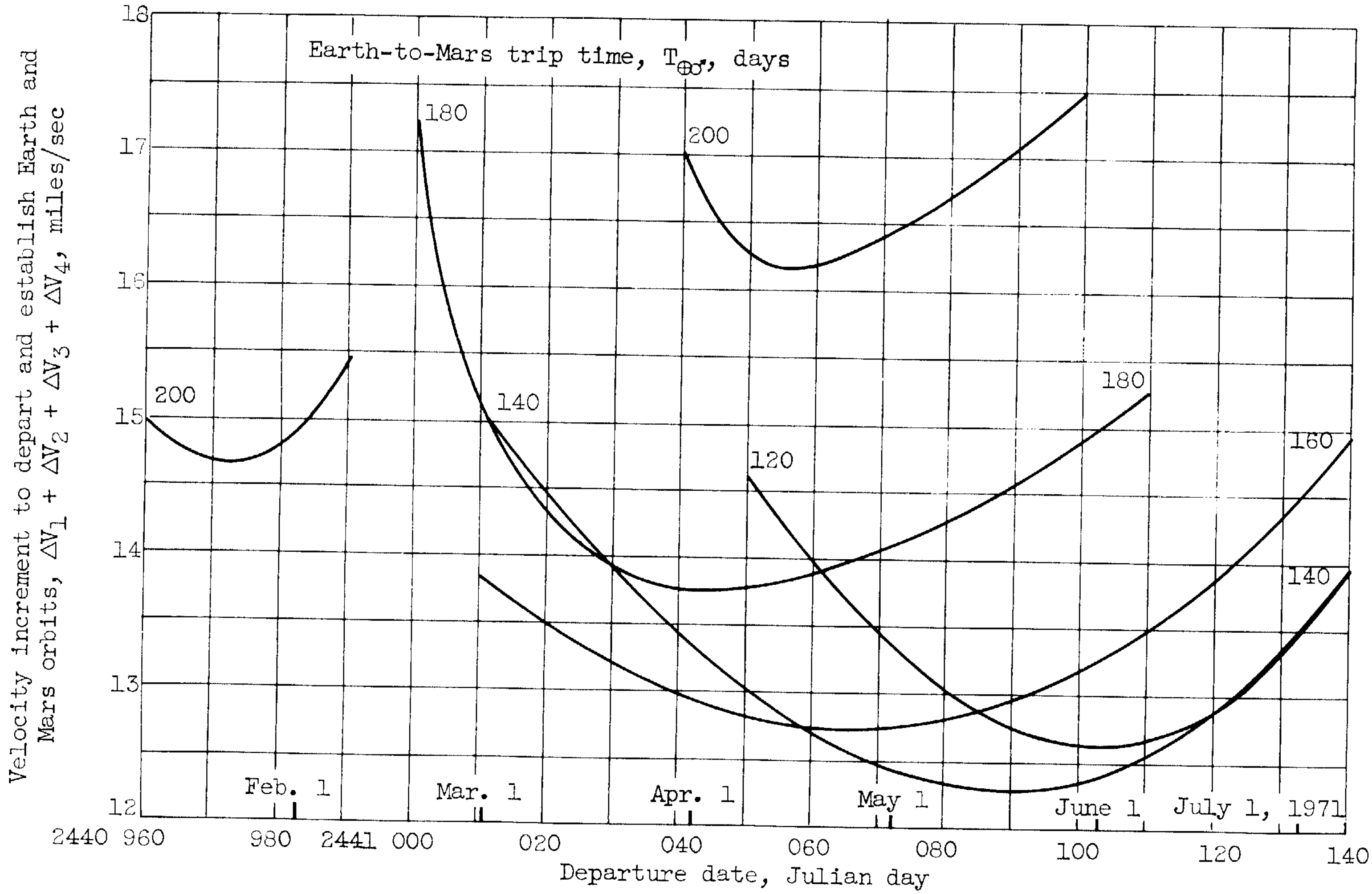
(a) Atmospheric braking at Mars and Earth.

Figure 6. - Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



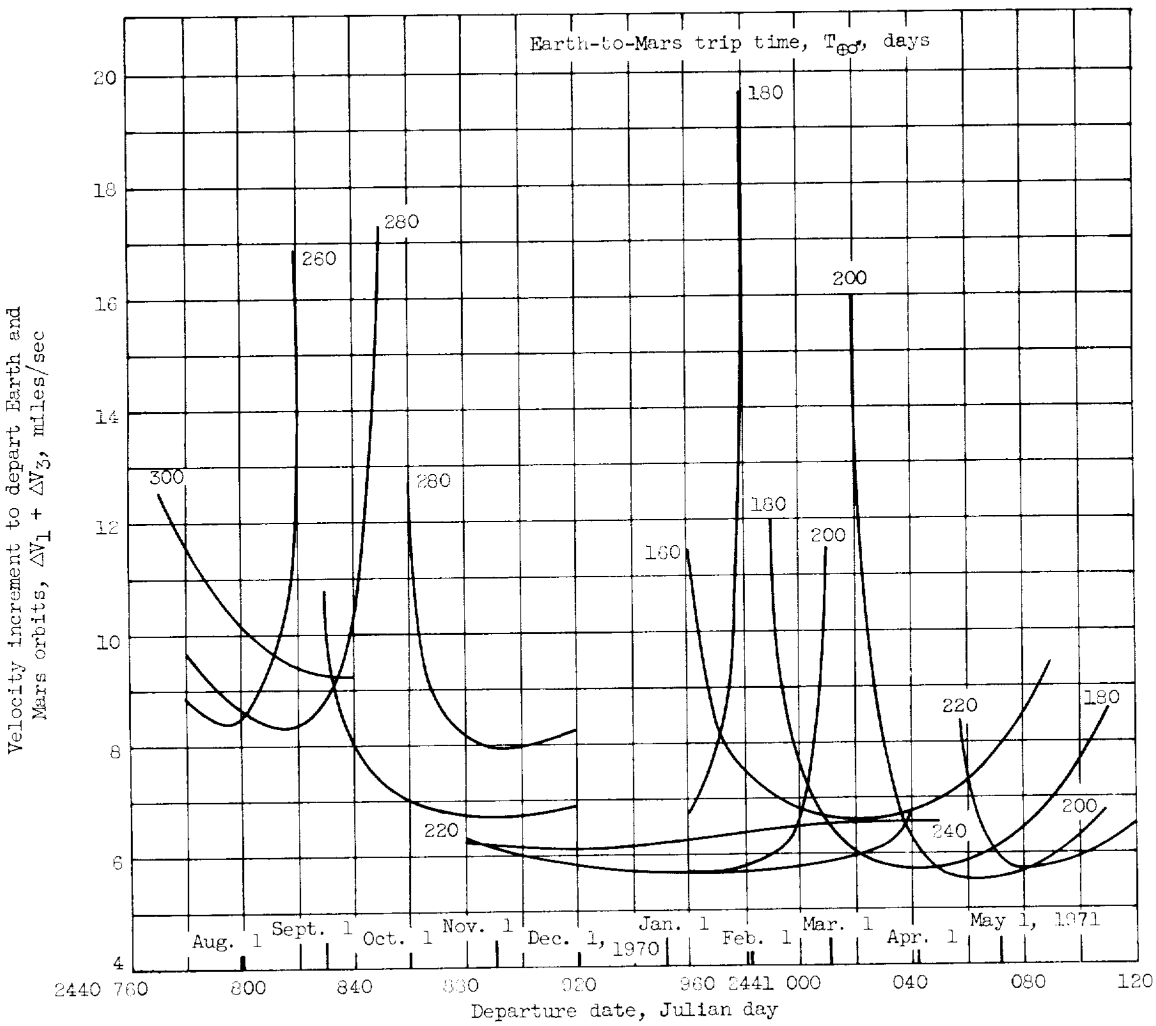
(b) Atmospheric braking at Earth.

Figure 6. - Continued. Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



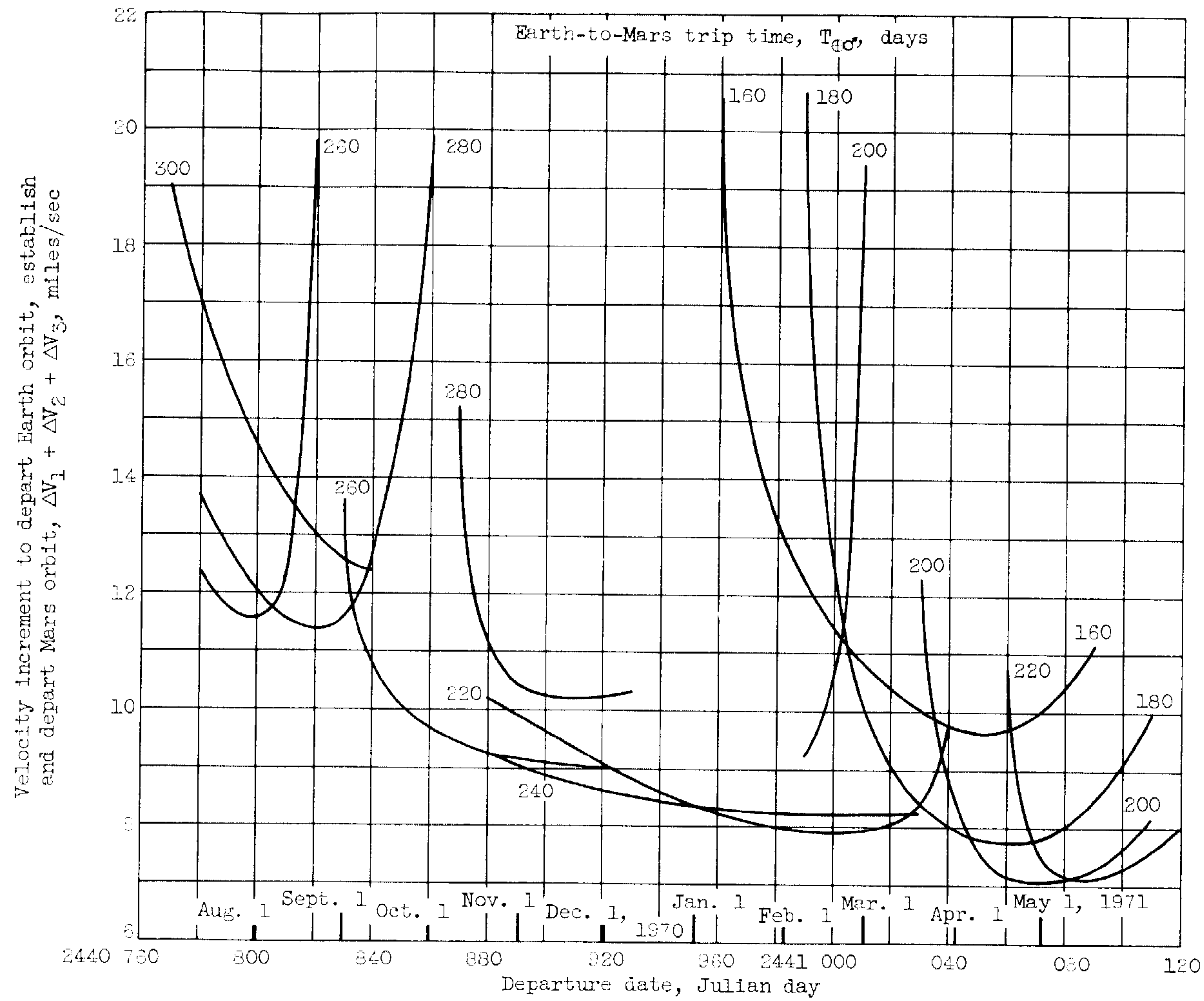
(c) All propulsive braking.

Figure 6. - Concluded. Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



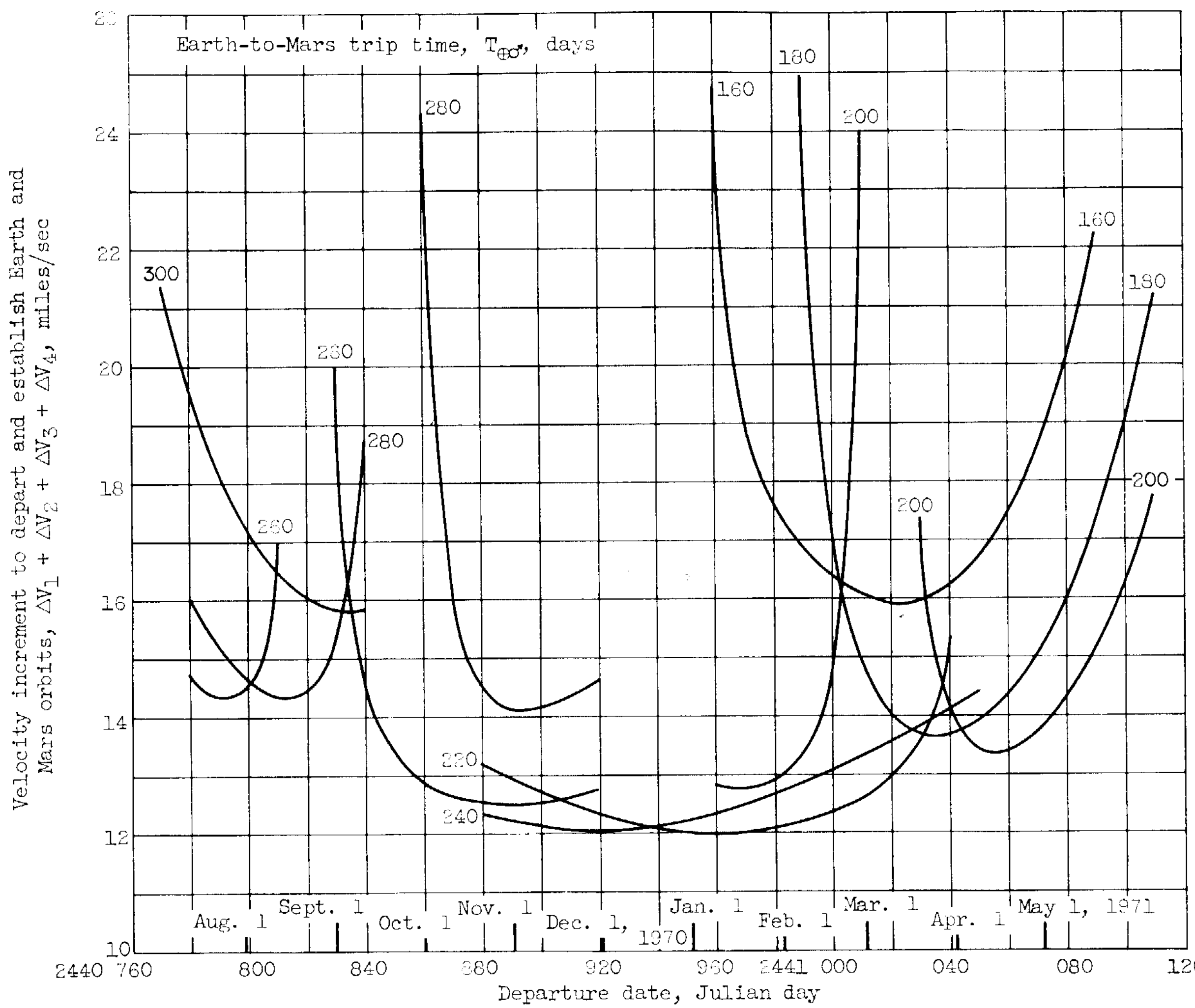
(a) Atmospheric braking at Mars and Earth.

Figure 7. - Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



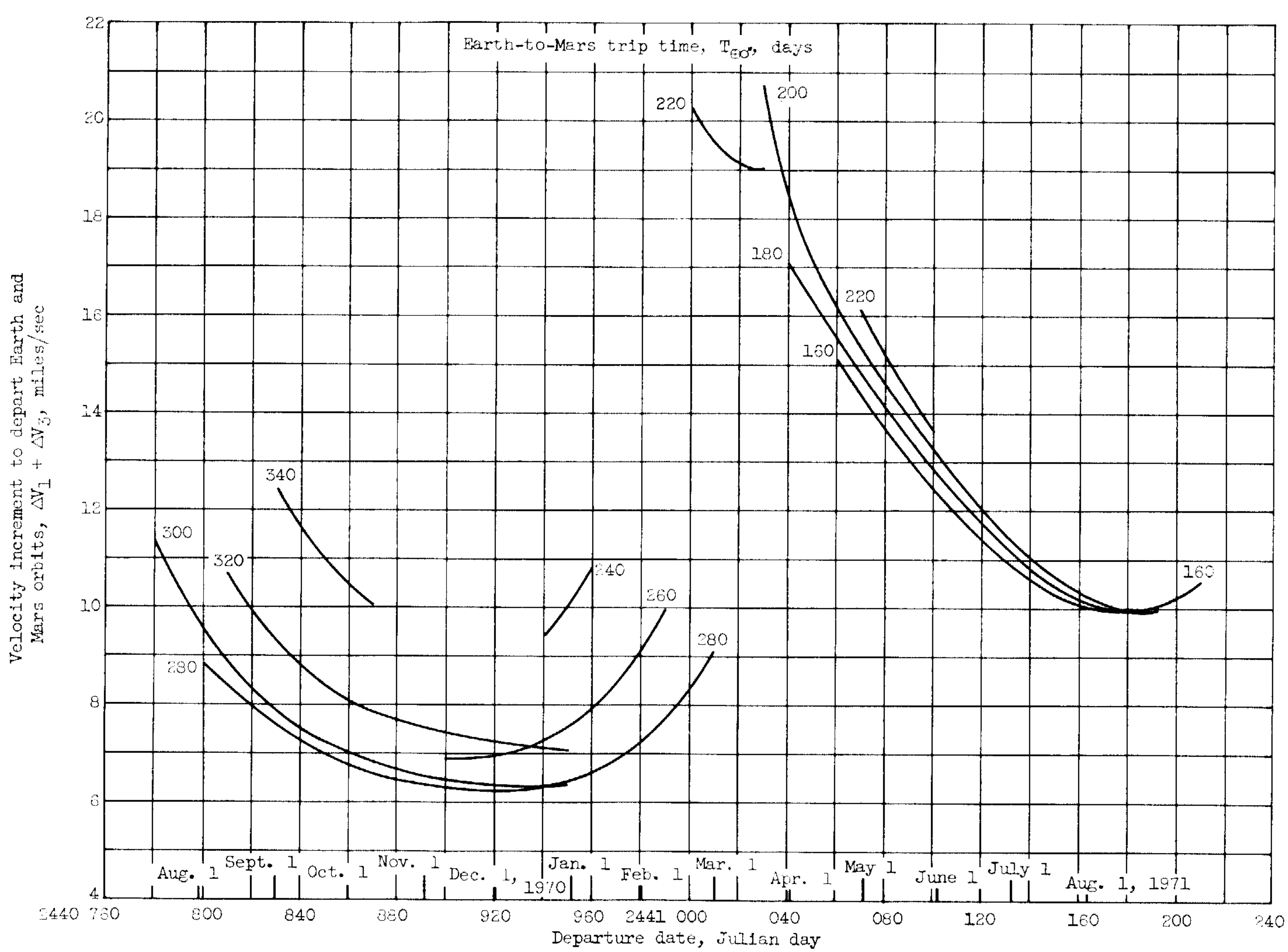
(b) Atmospheric braking at Earth.

Figure 7. - Continued. Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



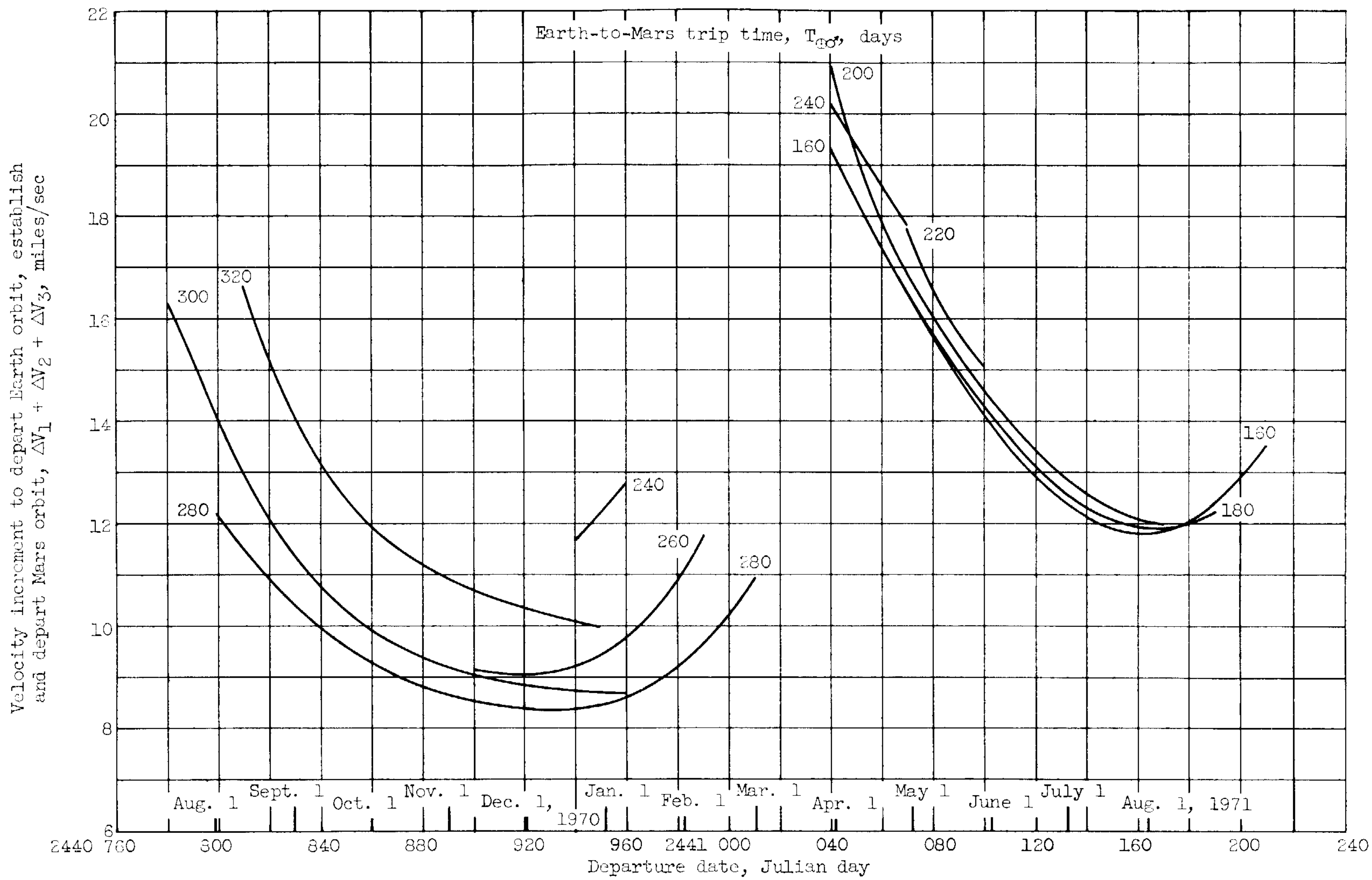
(c) All propulsive braking.

Figure 7. - Concluded. Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



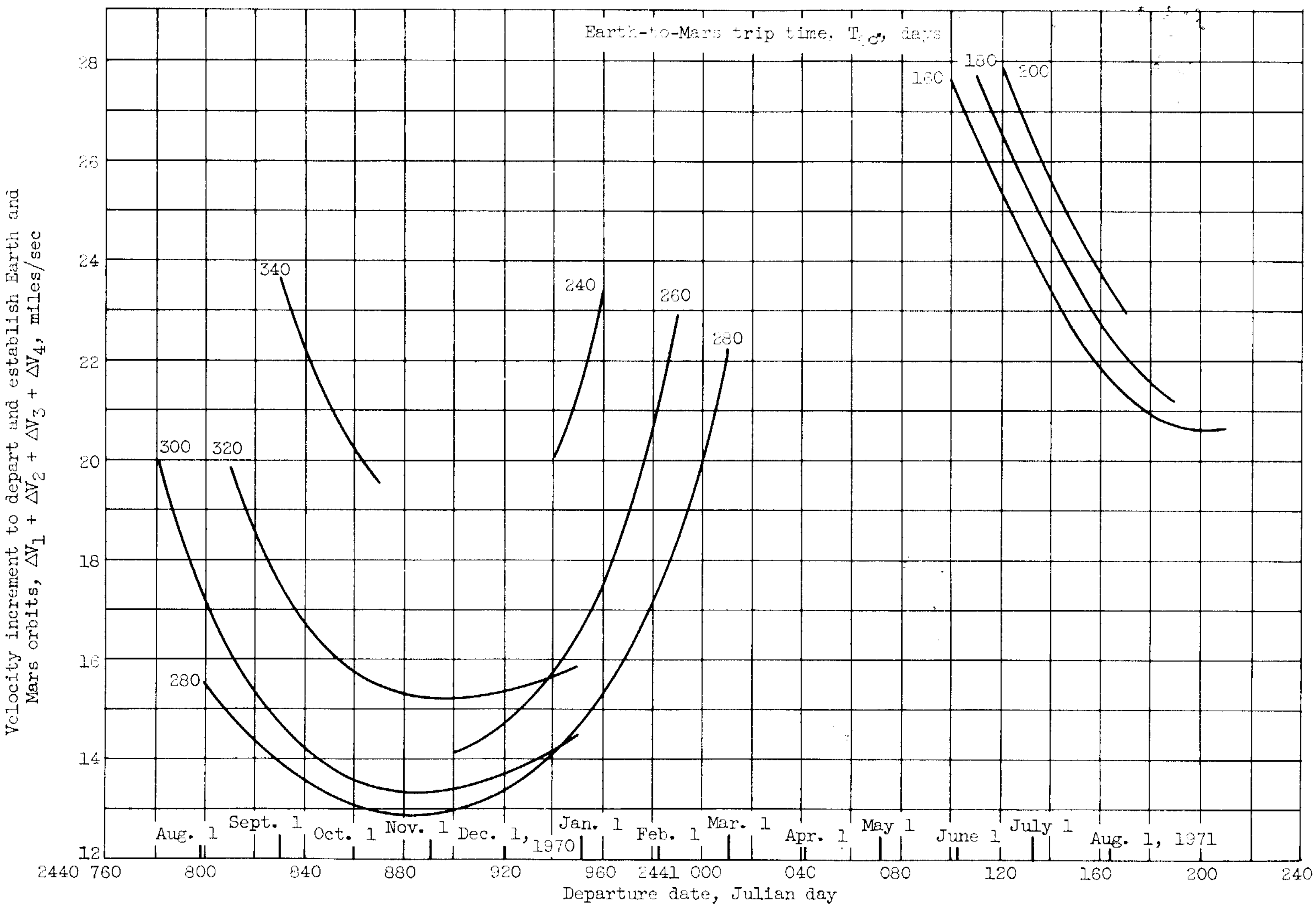
(a) Atmospheric braking at Mars and Earth

Figure 3. - Velocity increments for 600-day round trip to Mars. Wait time in Mars orbit, 40 days.



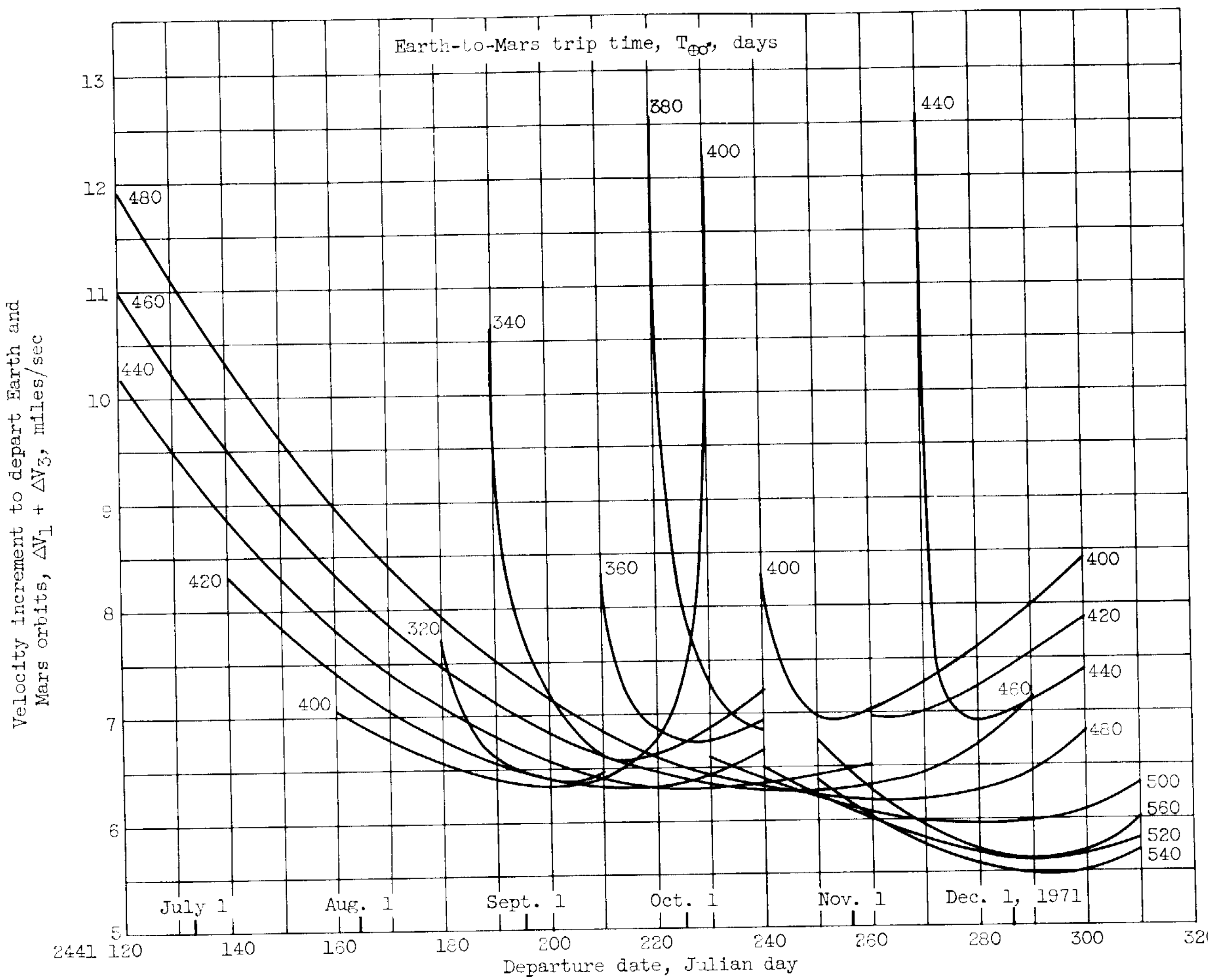
(b) Atmospheric braking at Earth.

Figure 8. - Continued. Velocity increments for 600-day round trip to Mars. Wait time in Mars orbit, 40 days.



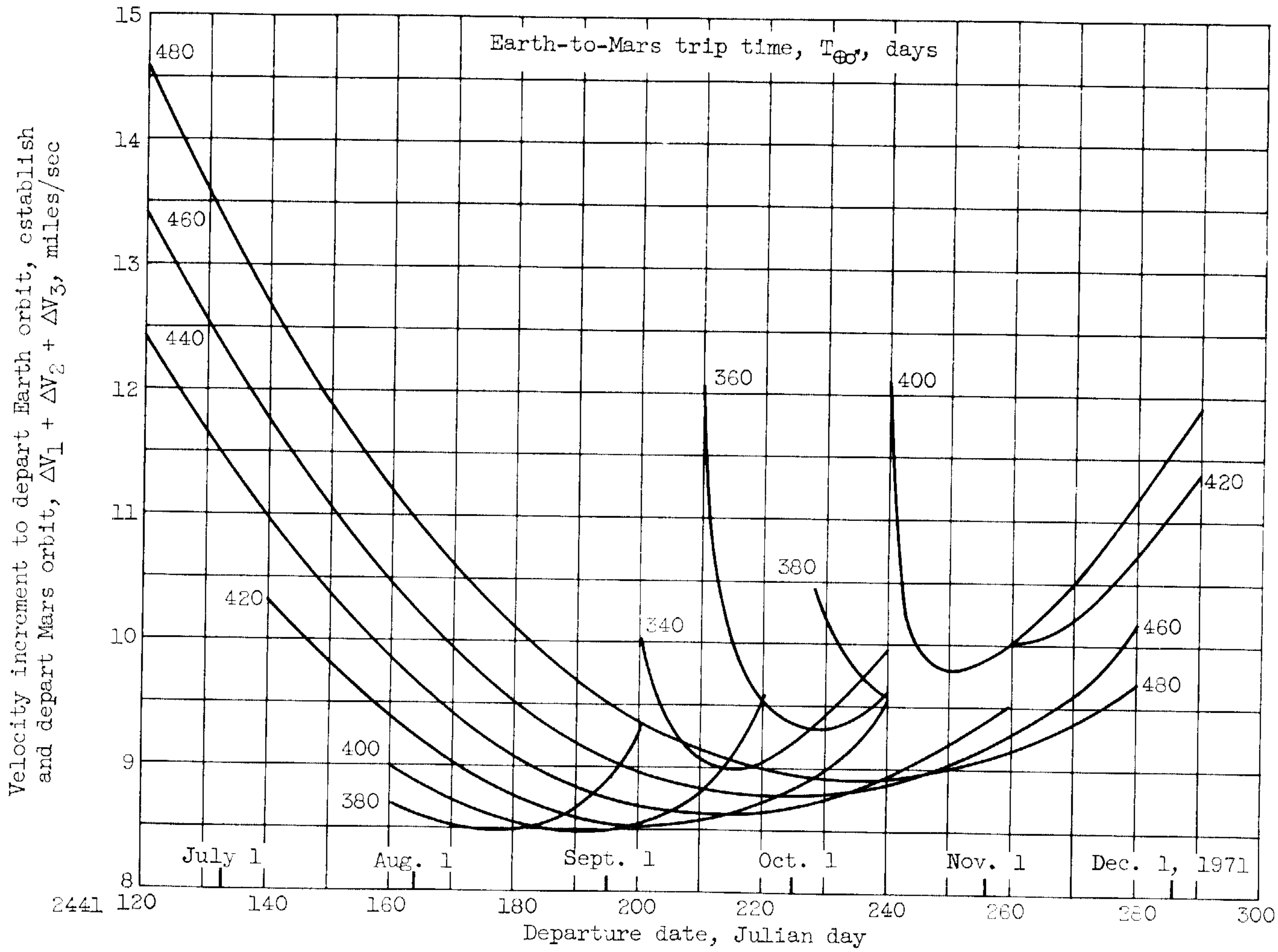
(c) All propulsive braking.

Figure 8. - Concluded. Velocity increments for 600-day round trip to Mars. Wait time in Mars orbit, 40 days.



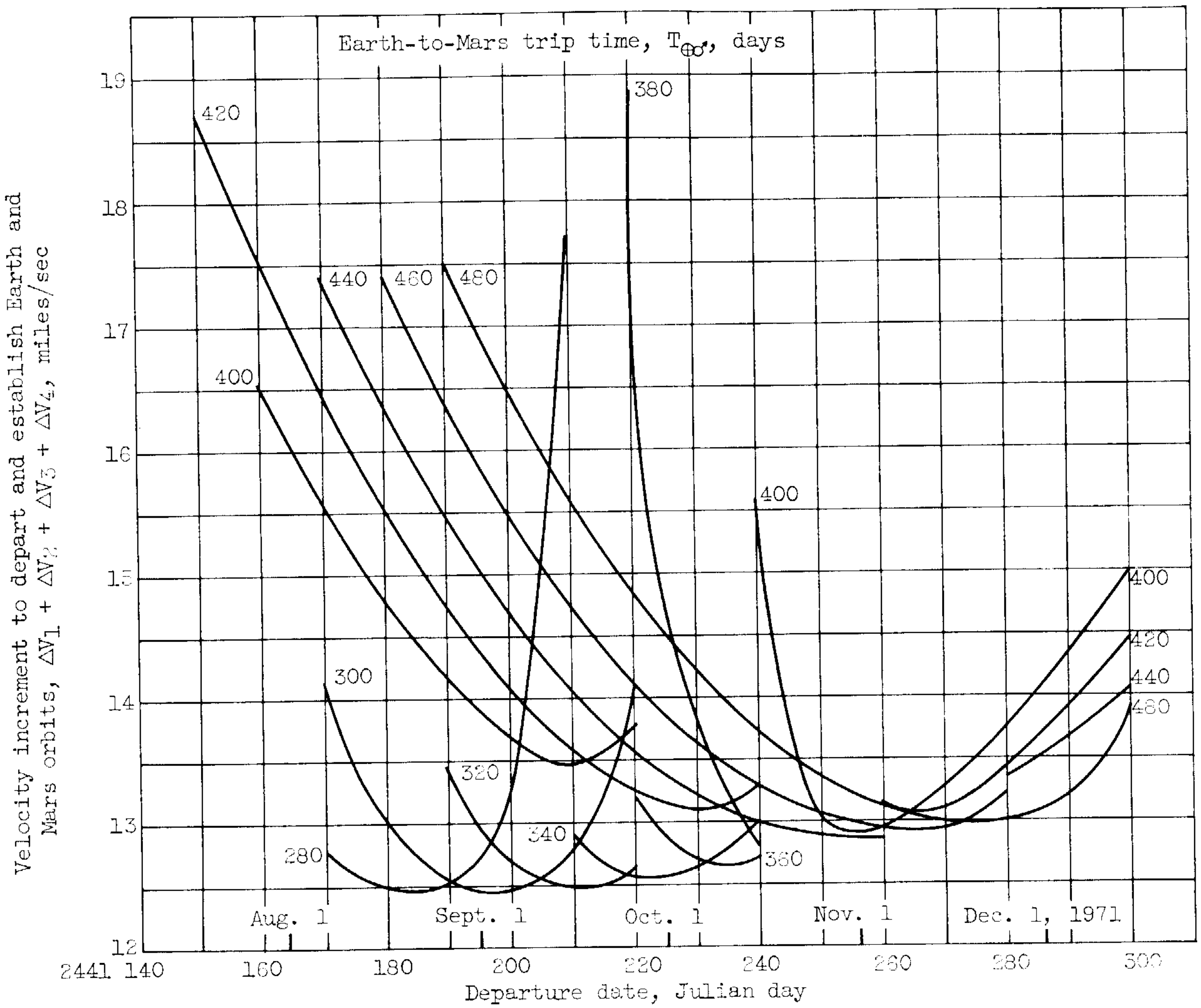
(a) Atmospheric braking at Mars and Earth.

Figure 9. - Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 40 days.



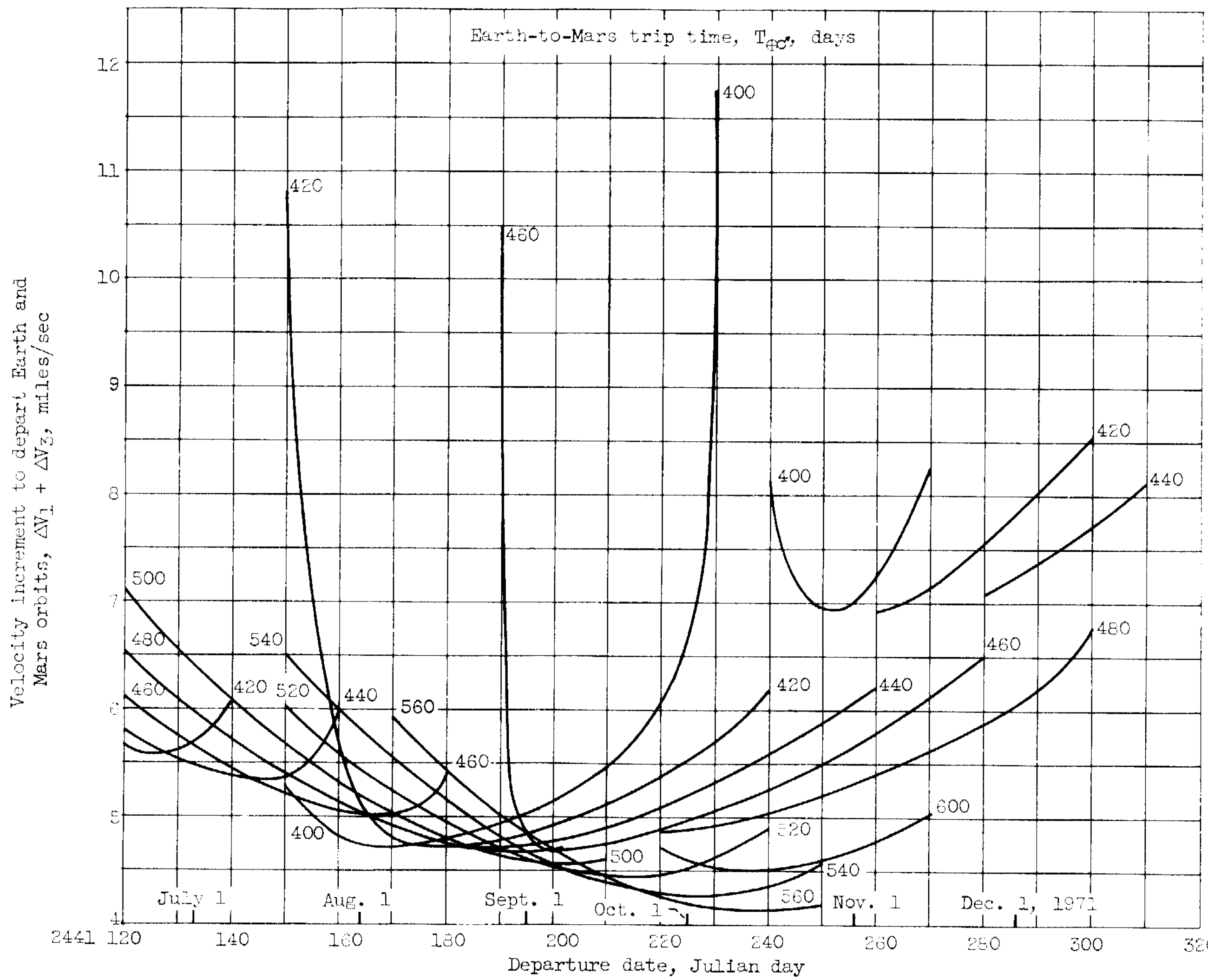
(b) Atmospheric braking at Earth.

Figure 9. - Continued. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 40 days.



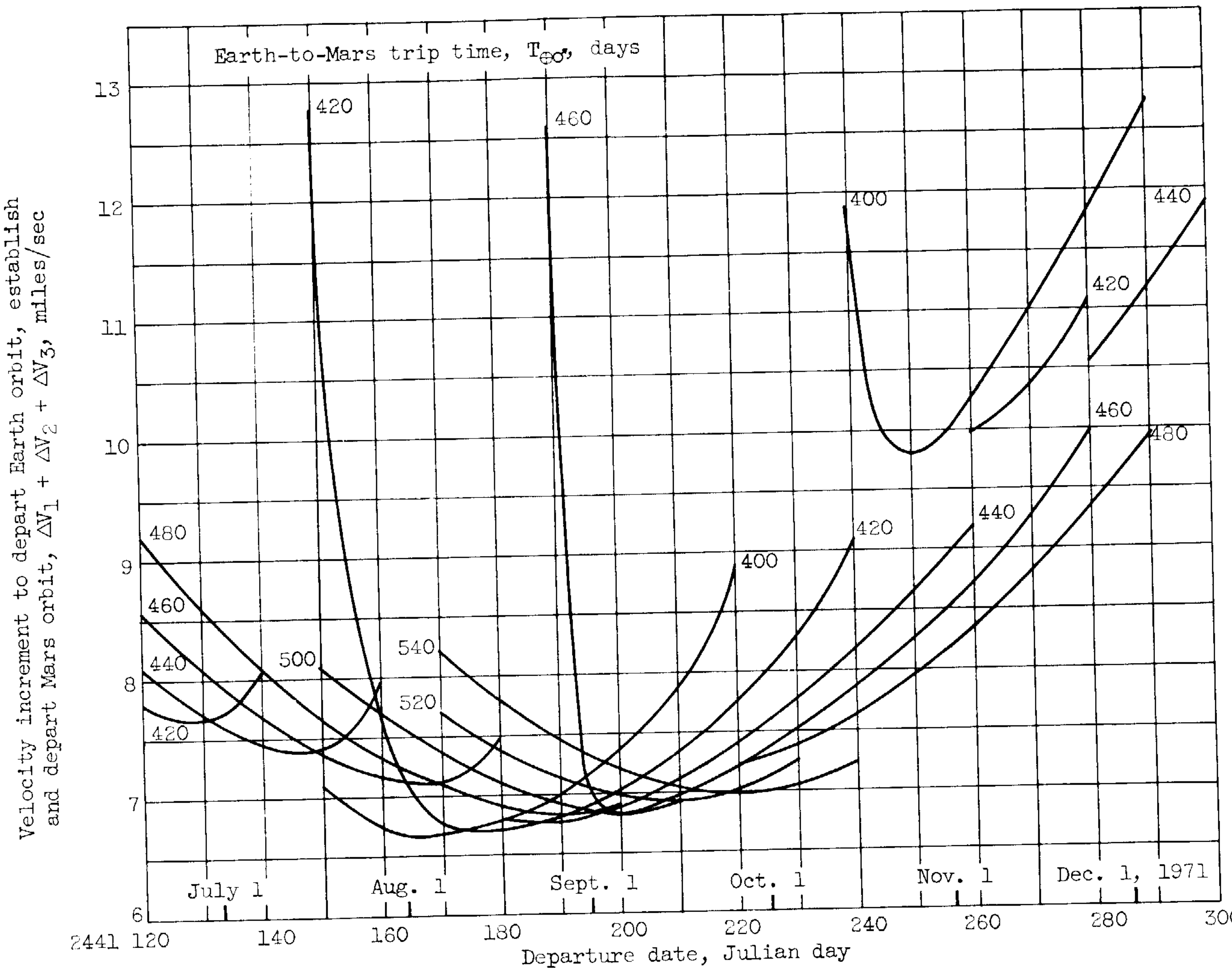
(c) All propulsive braking.

Figure 9. - Concluded. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 40 days.



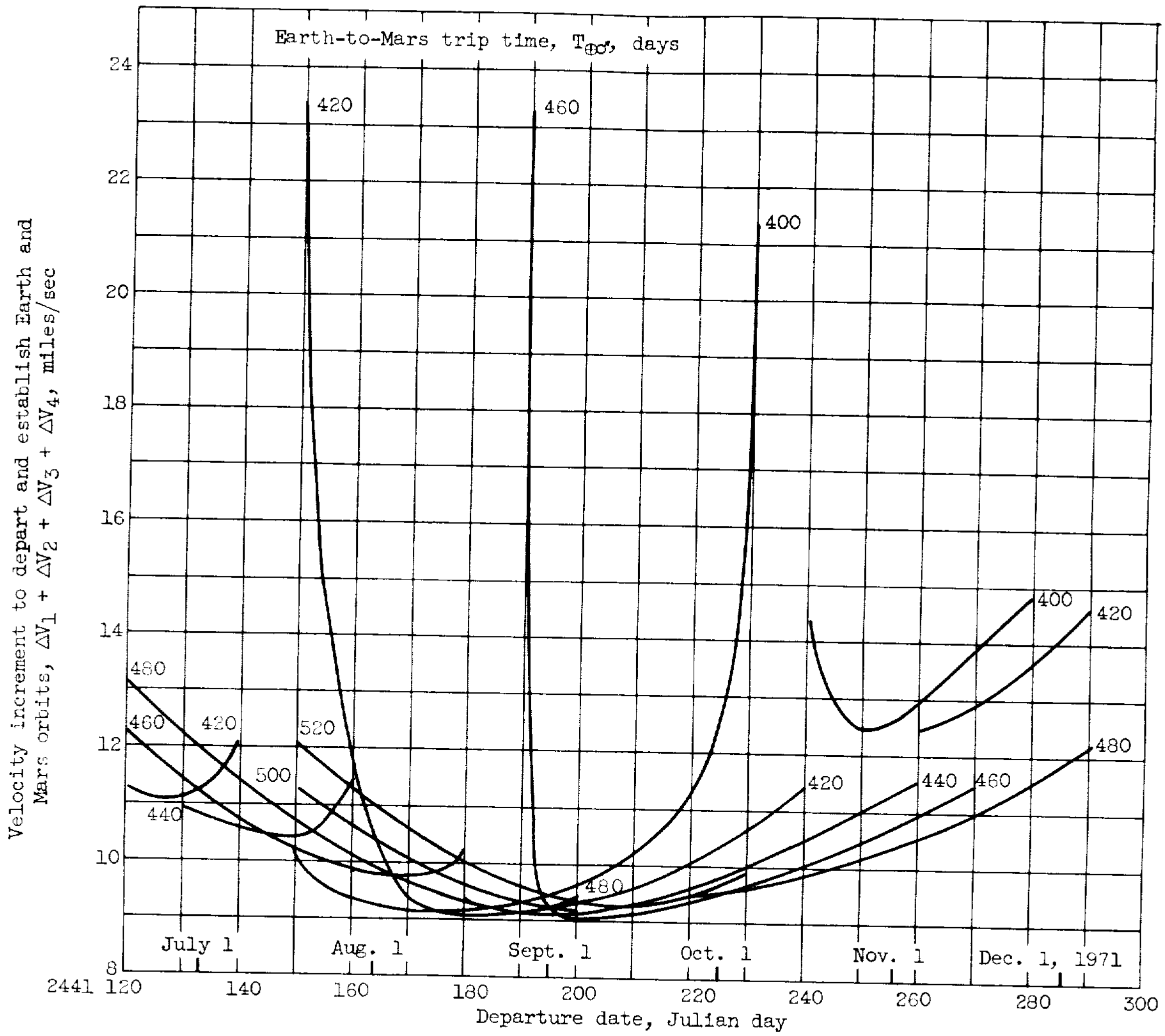
(a) Atmospheric braking at Mars and Earth.

Figure 10. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.



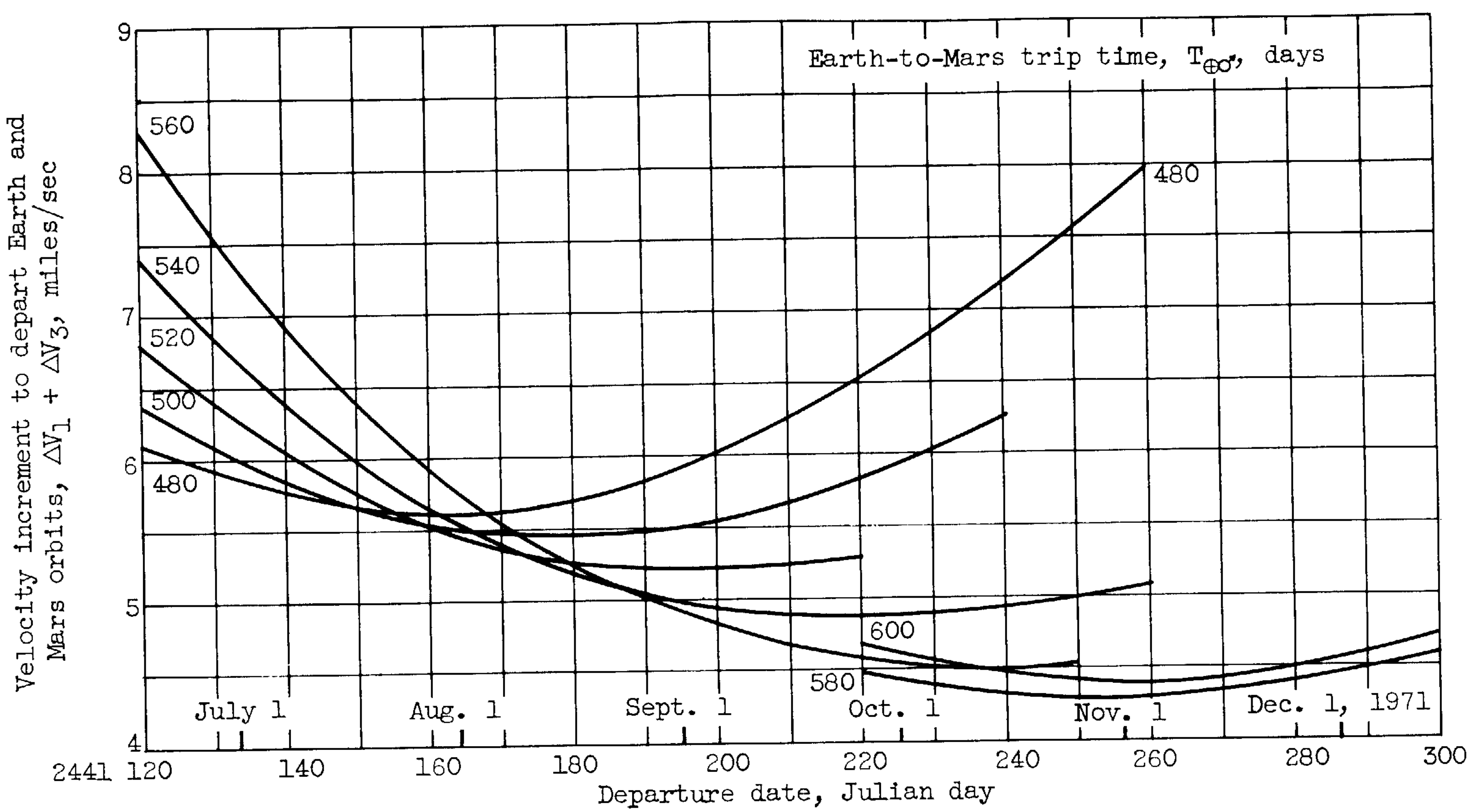
(b) Atmospheric braking at Earth.

Figure 10. - Continued. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.



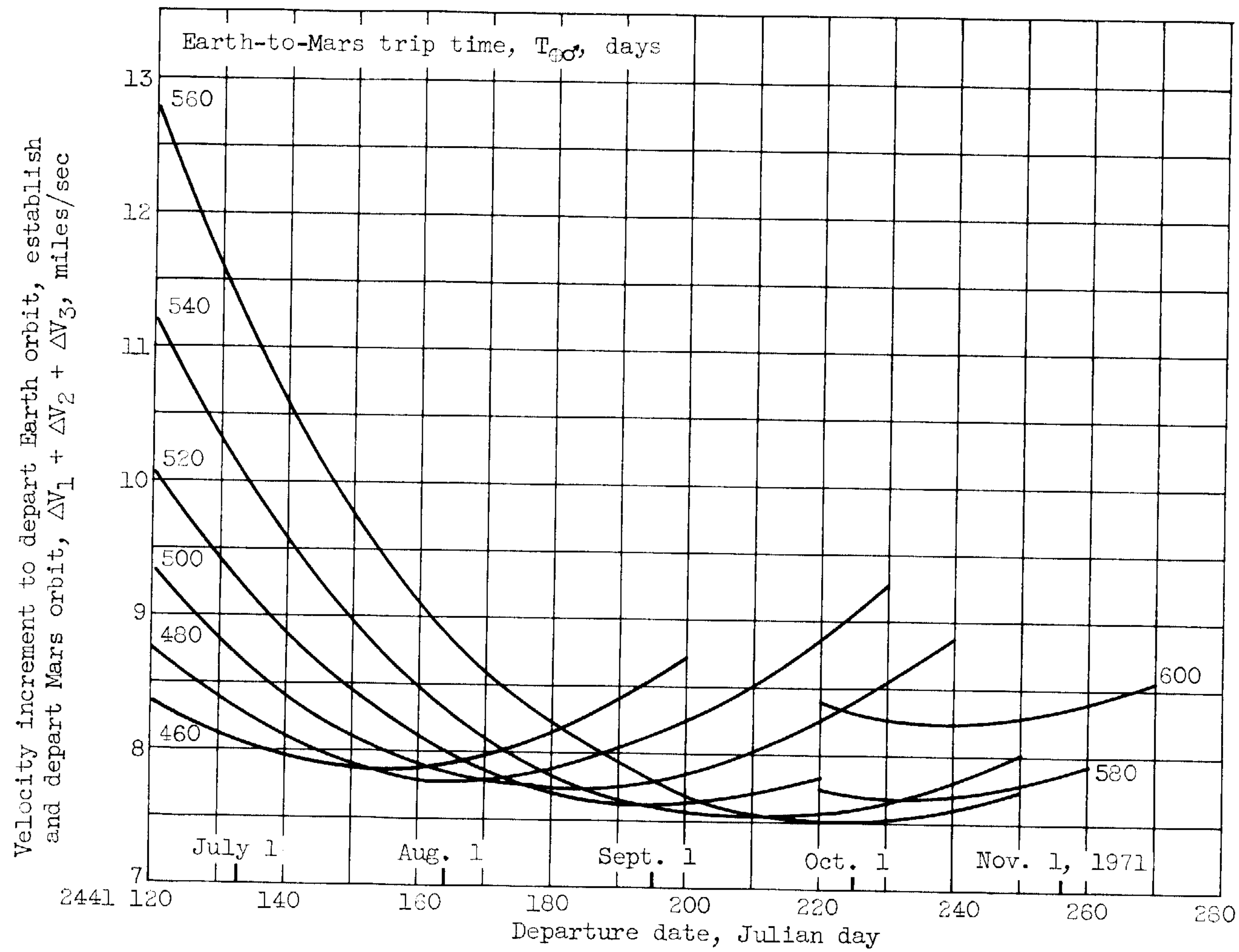
(c) All propulsive braking.

Figure 10. - Concluded. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.



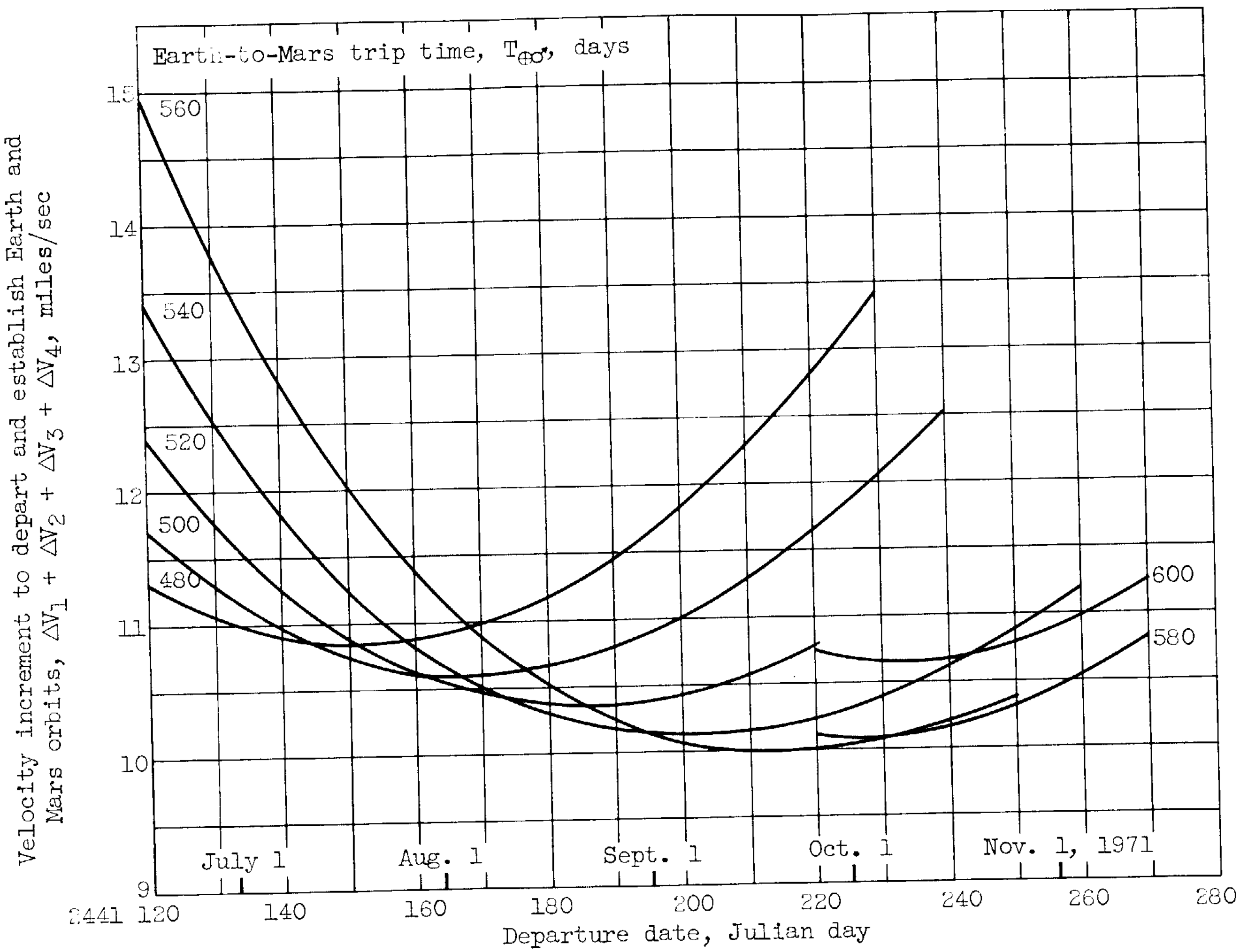
(a) Atmospheric braking at Mars and Earth.

Figure 11. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 40 days.



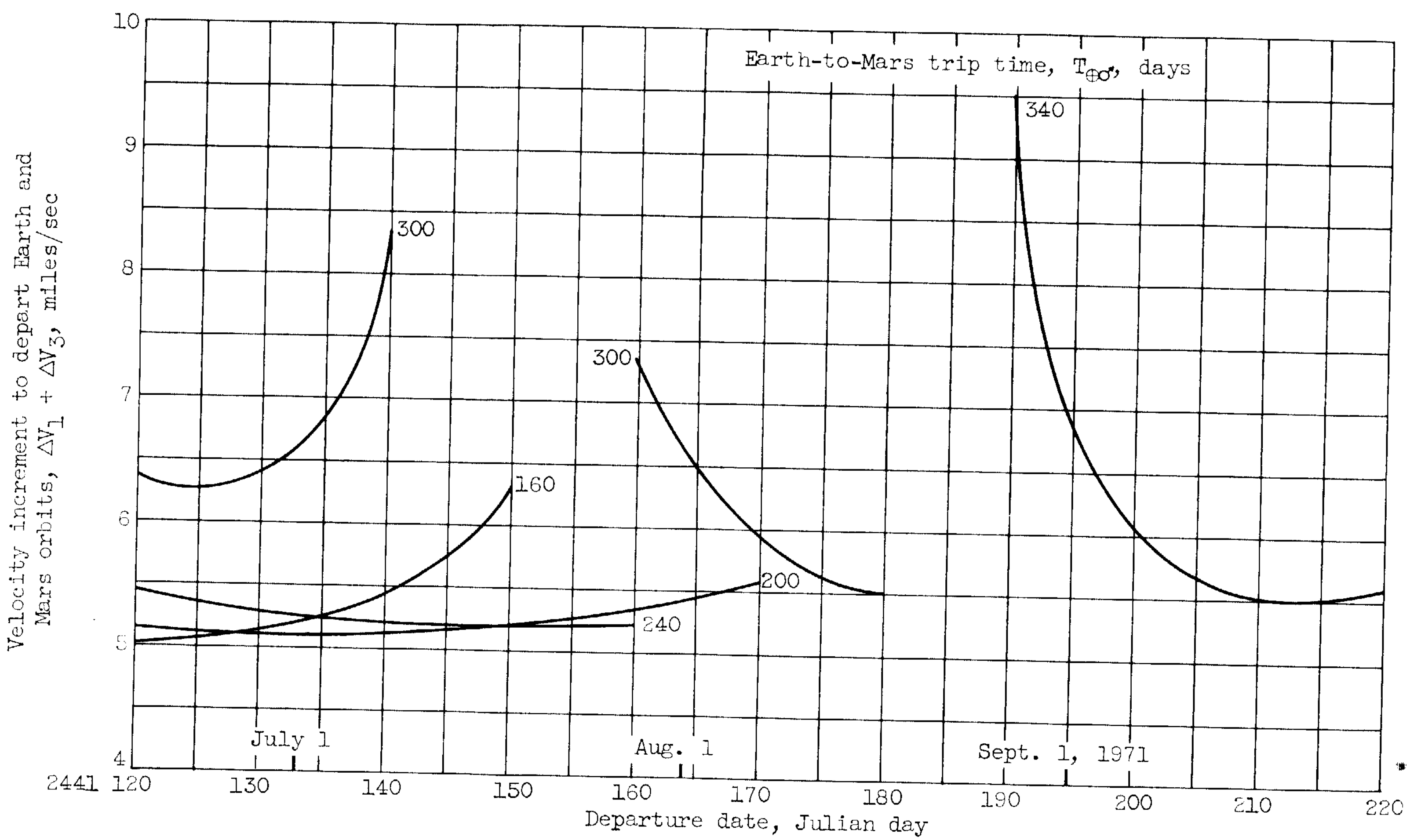
(b) Atmospheric braking at Earth.

Figure 11. - Continued. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 40 days.



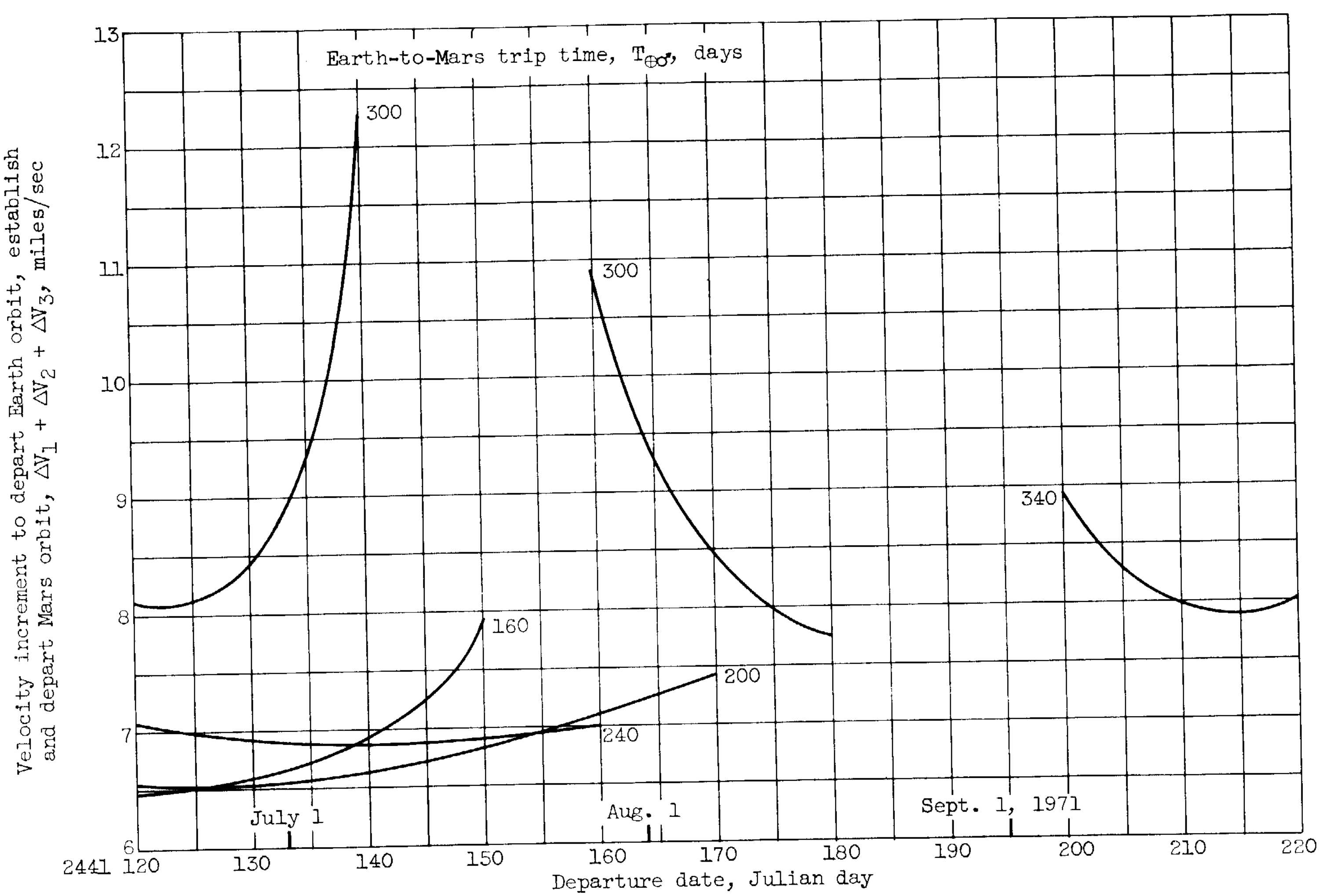
(c) All propulsive braking.

Figure 11. - Concluded. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 40 days.



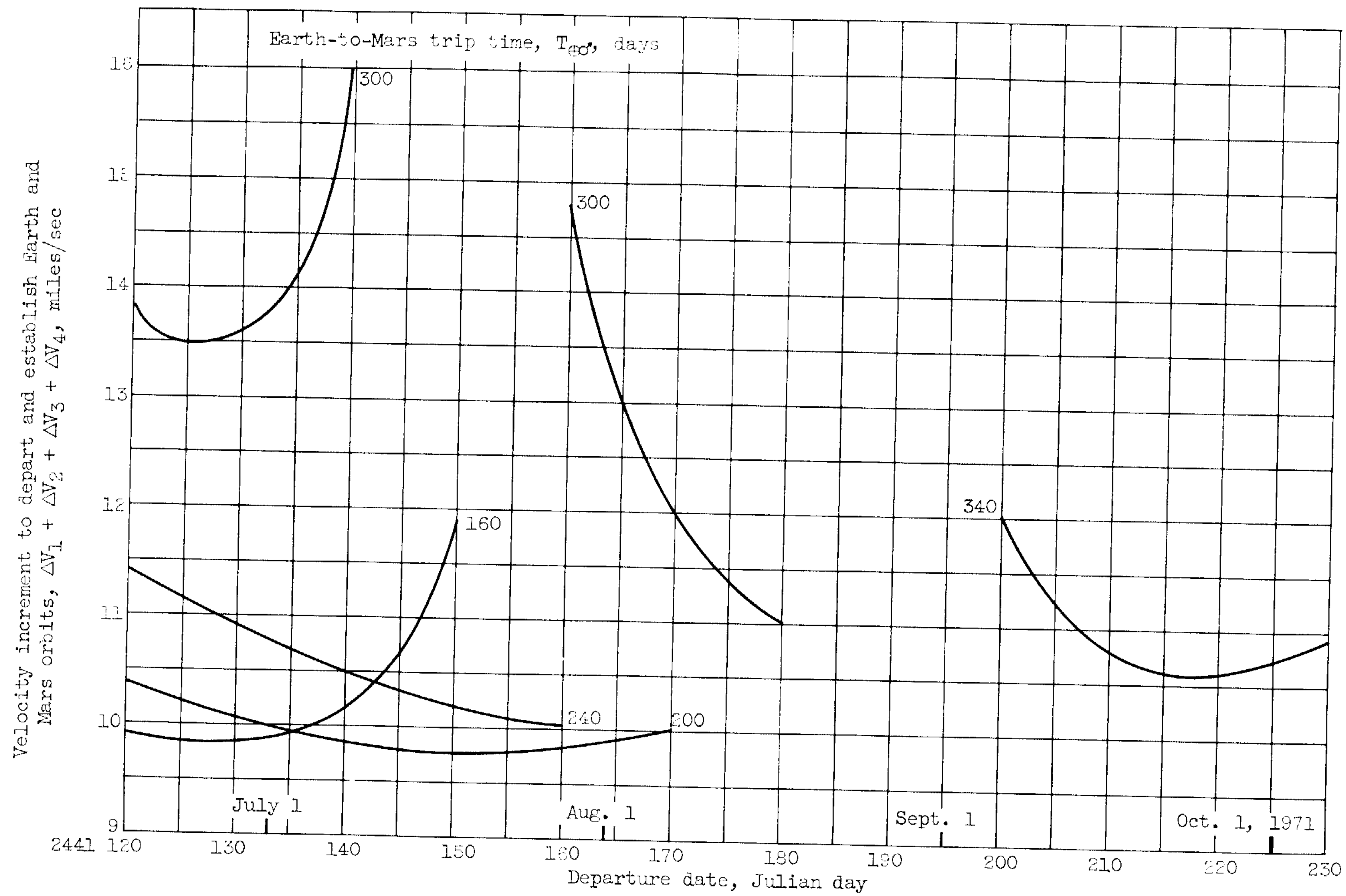
(a) Atmospheric braking at Mars and Earth.

Figure 12. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 310 days.



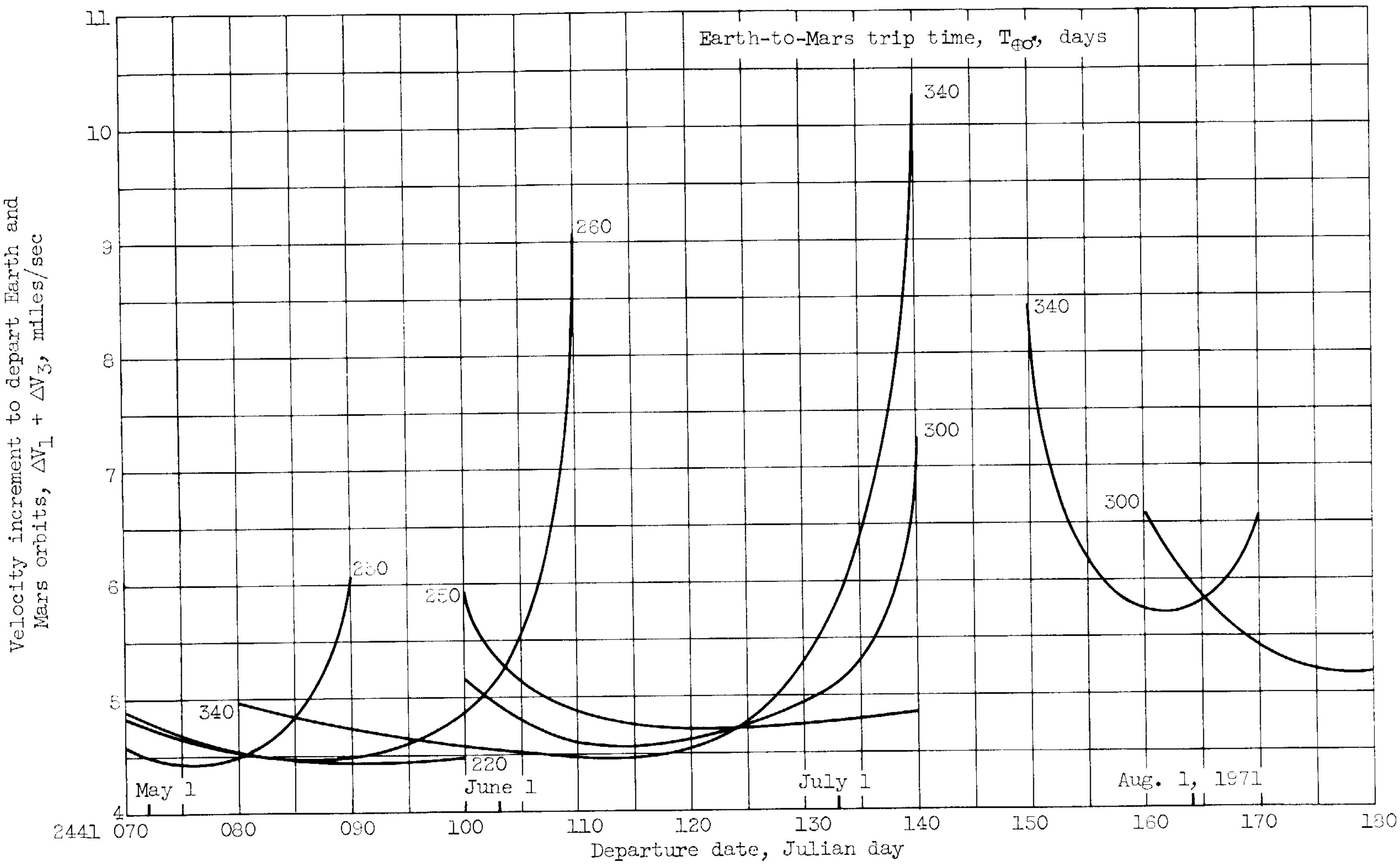
(b) Atmospheric braking at Earth.

Figure 12. - Continued. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 310 days.



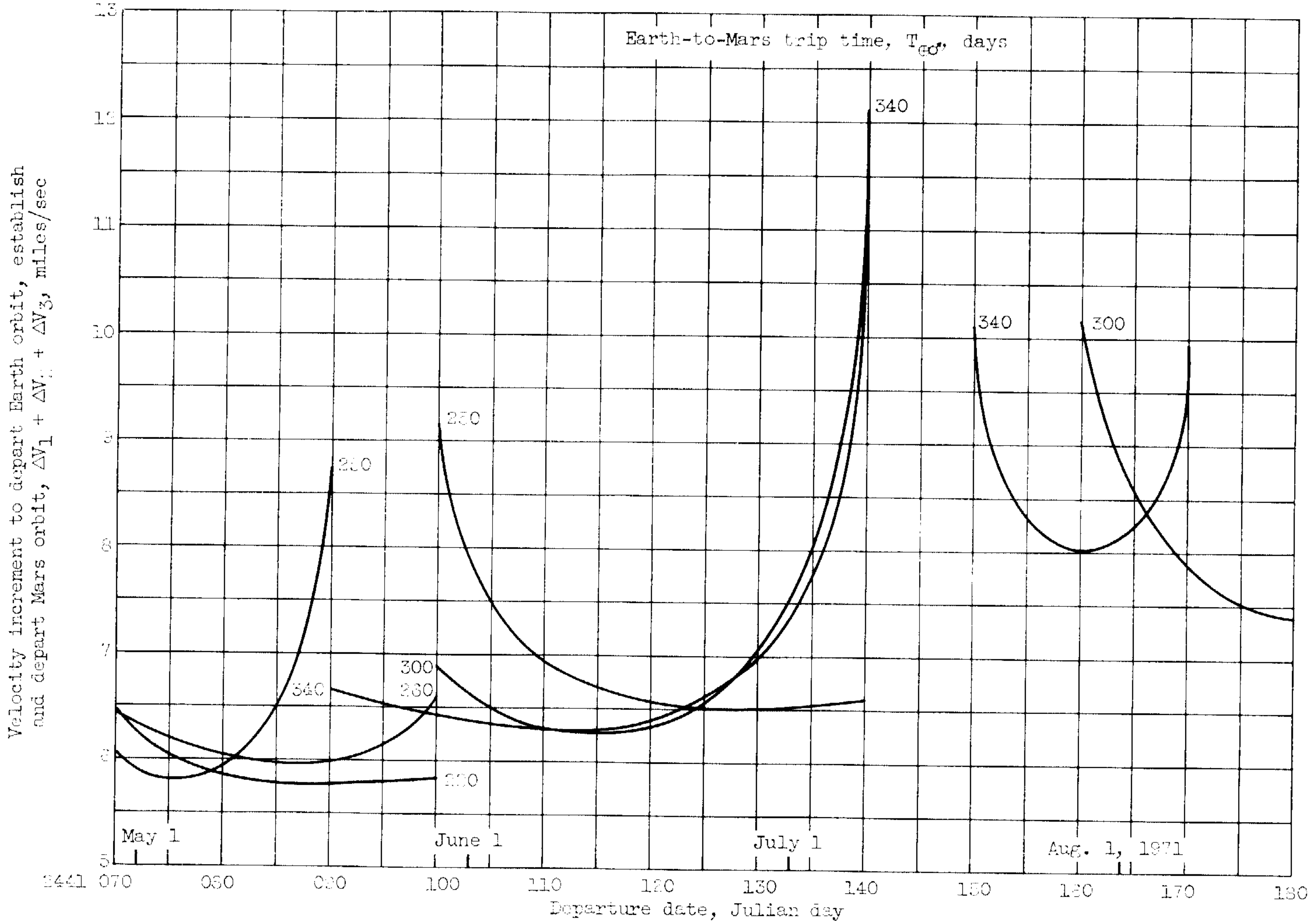
(c) All propulsive braking.

Figure 12. - Concluded. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 310 days.



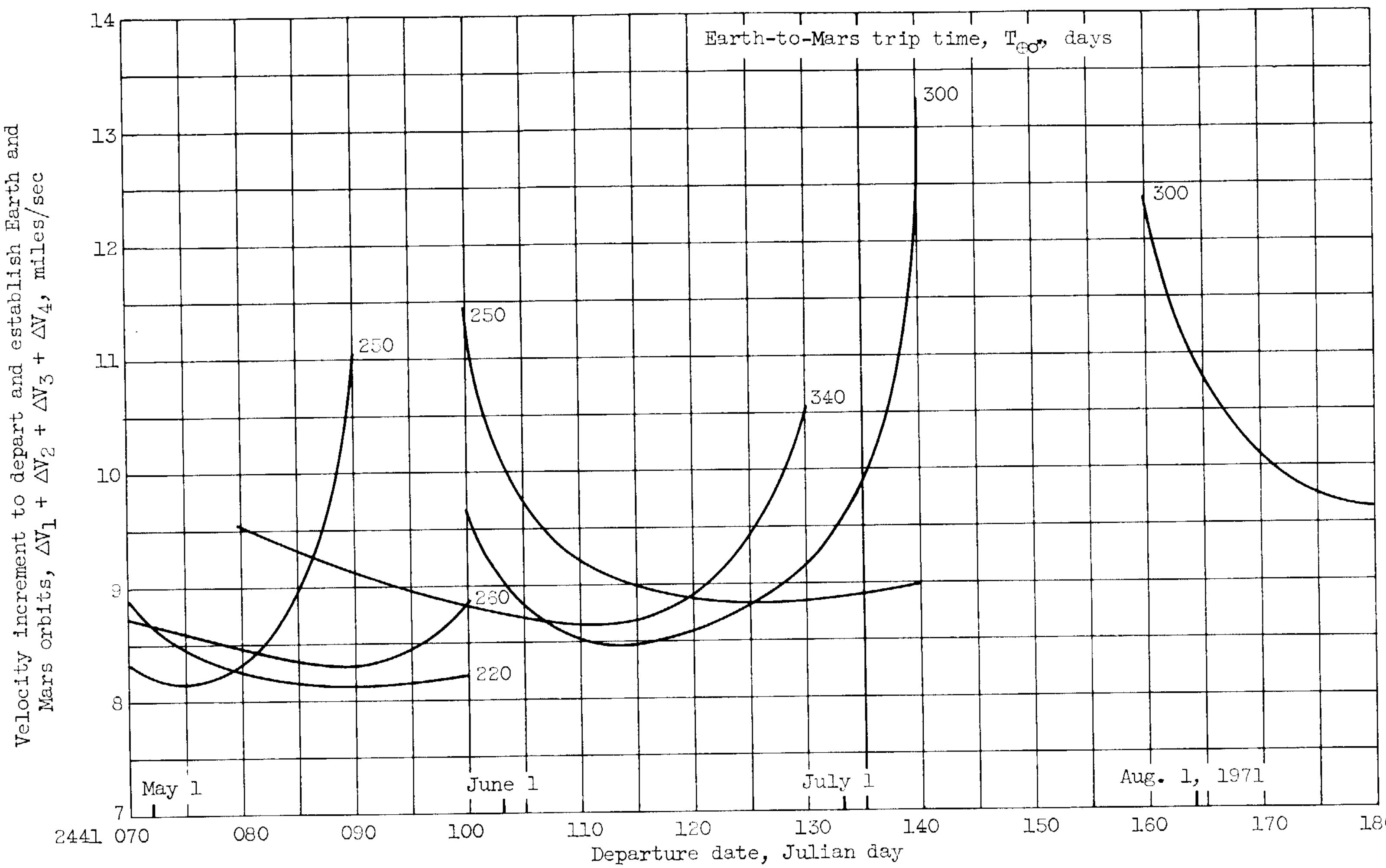
(a) Atmospheric braking at Mars and Earth.

Figure 13. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 310 days.



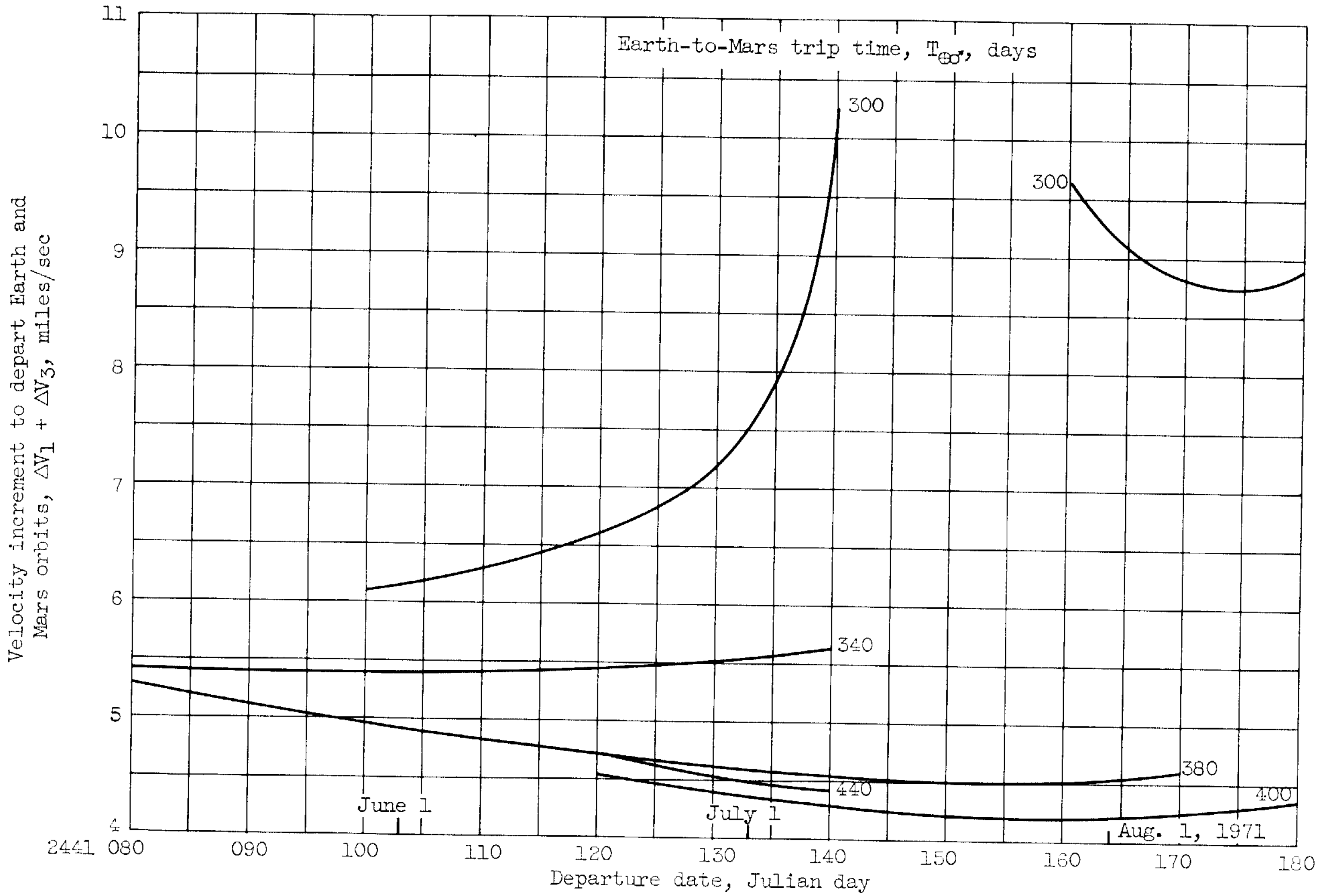
(b) Atmospheric braking at Earth.

Figure 13. - Continued. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 310 days.



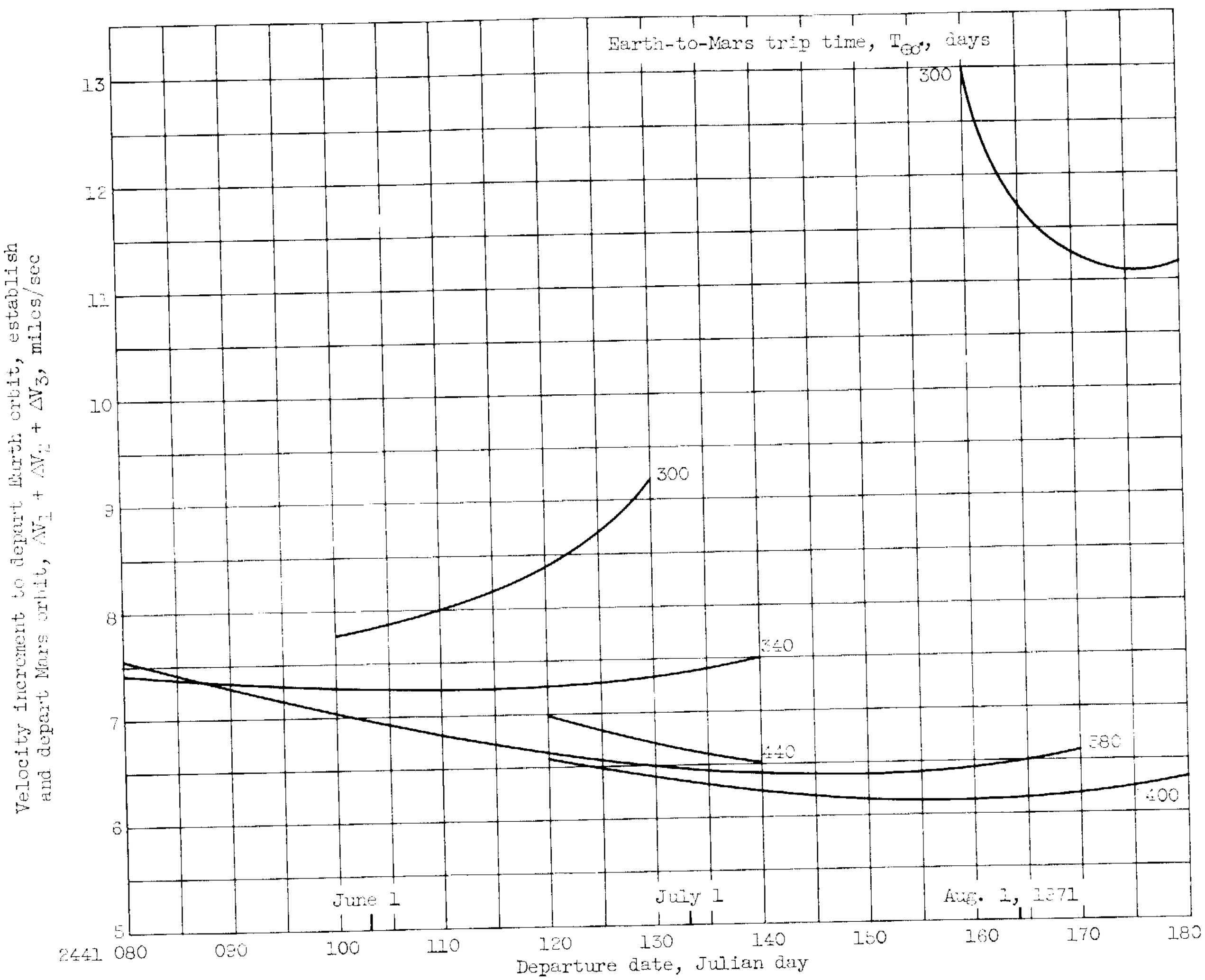
(c) All propulsive braking.

Figure 13. - Concluded. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 310 days.



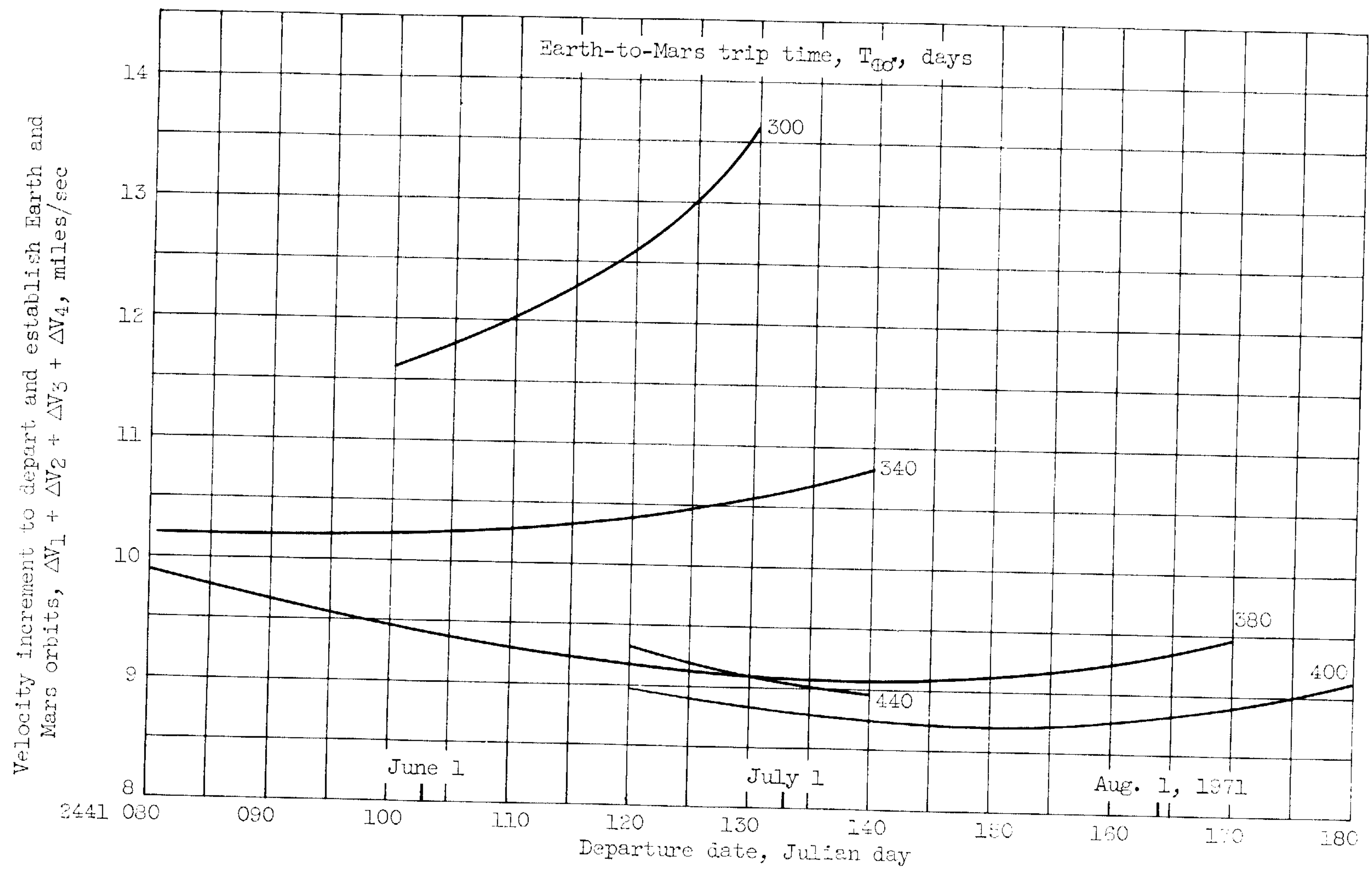
(a) Atmospheric braking at Mars and Earth.

Figure 14. - Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 310 days.



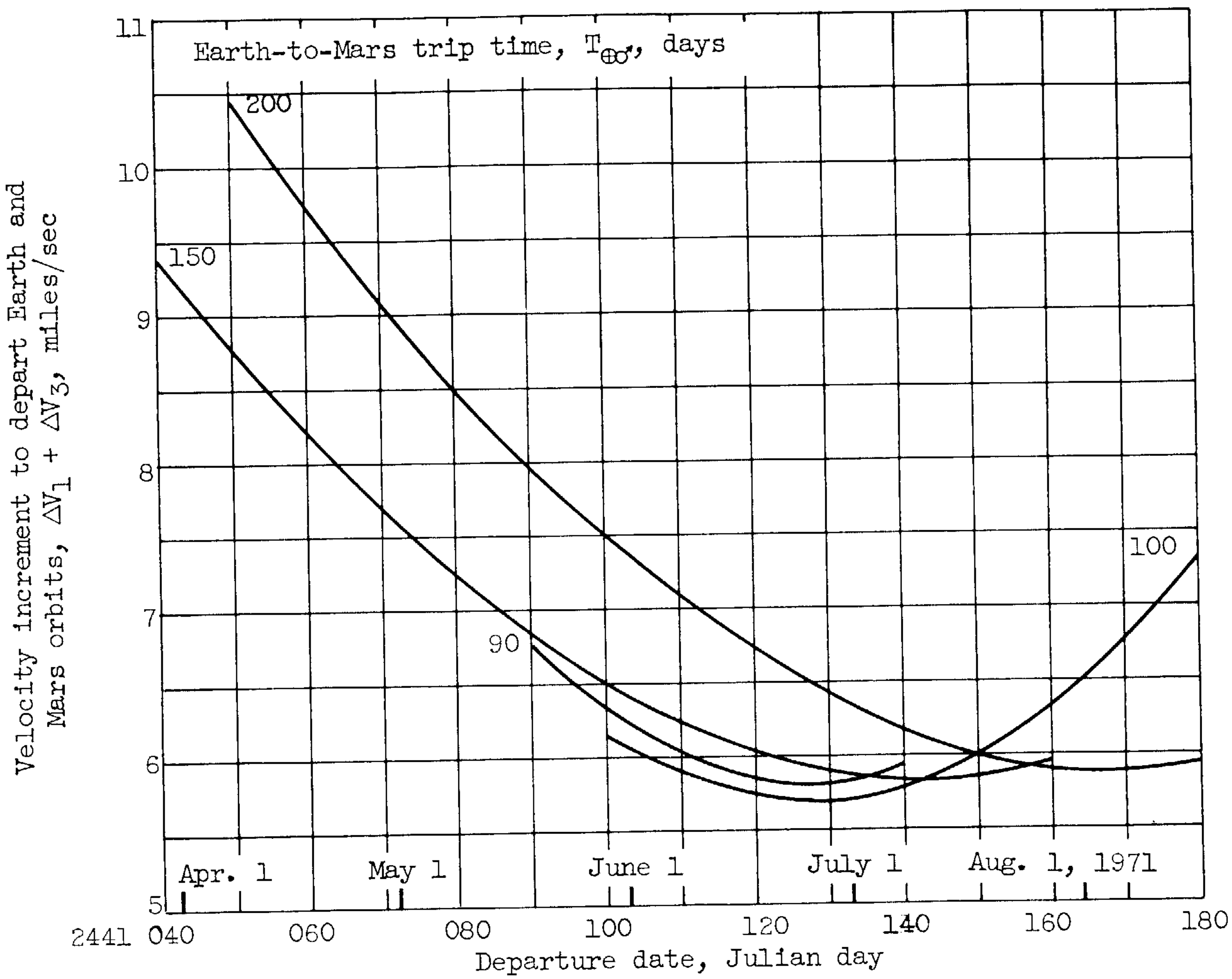
(b) Atmospheric braking at Earth.

Figure 14. - Continued. Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 310 days.



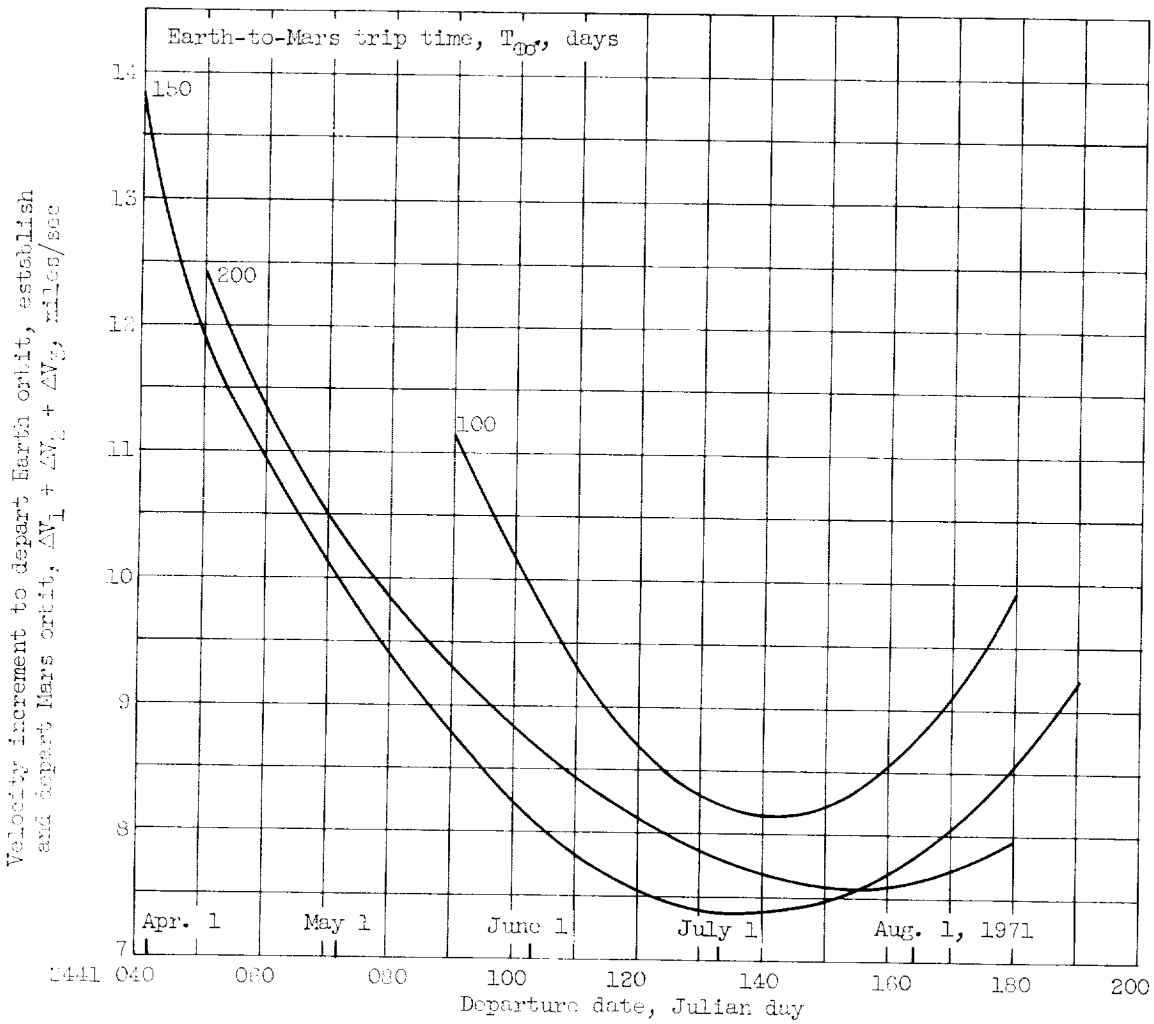
(c) All propulsive braking.

Figure 14. - Concluded. Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 310 days.



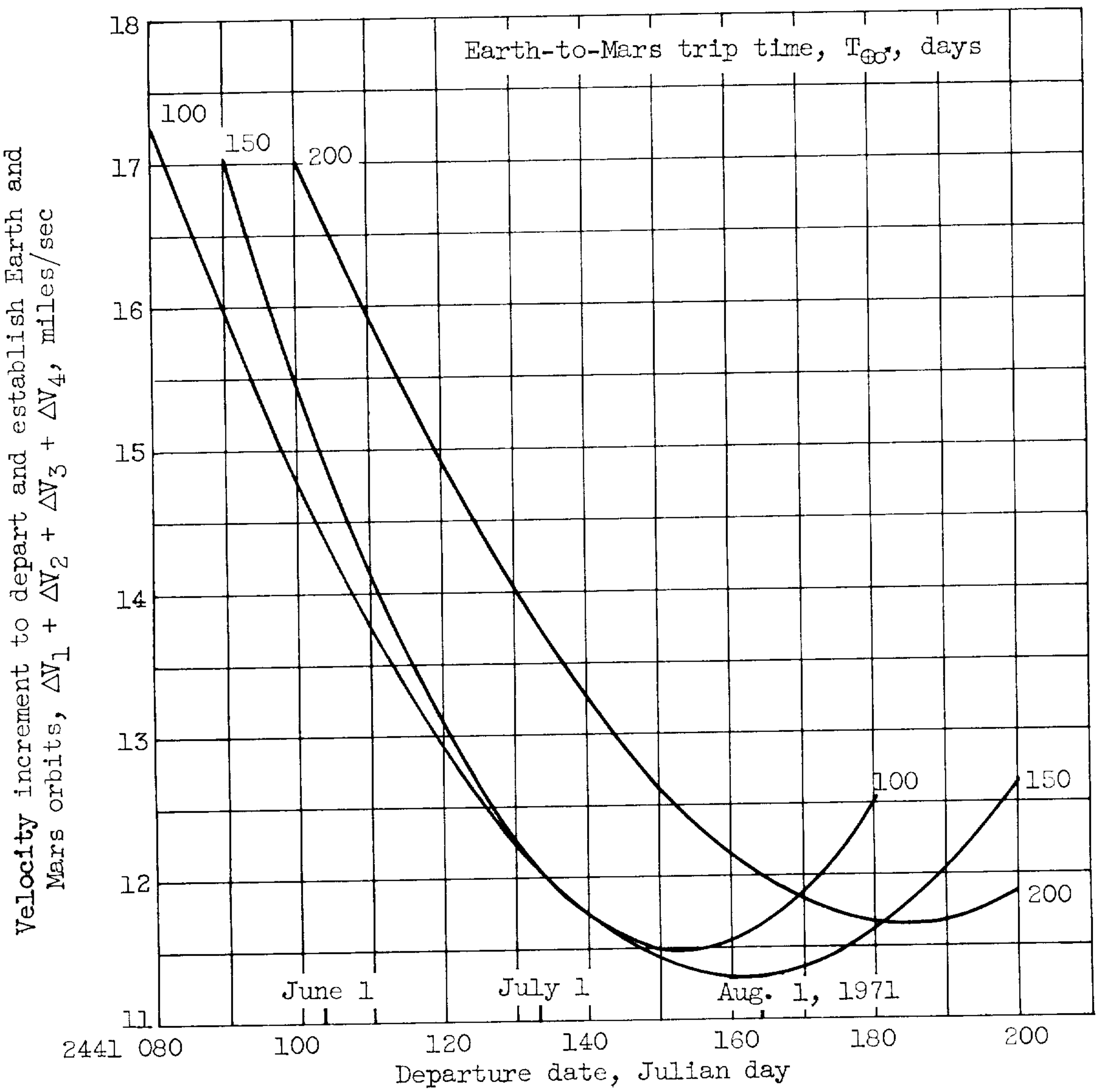
(a) Atmospheric braking at Mars and Earth.

Figure 15. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



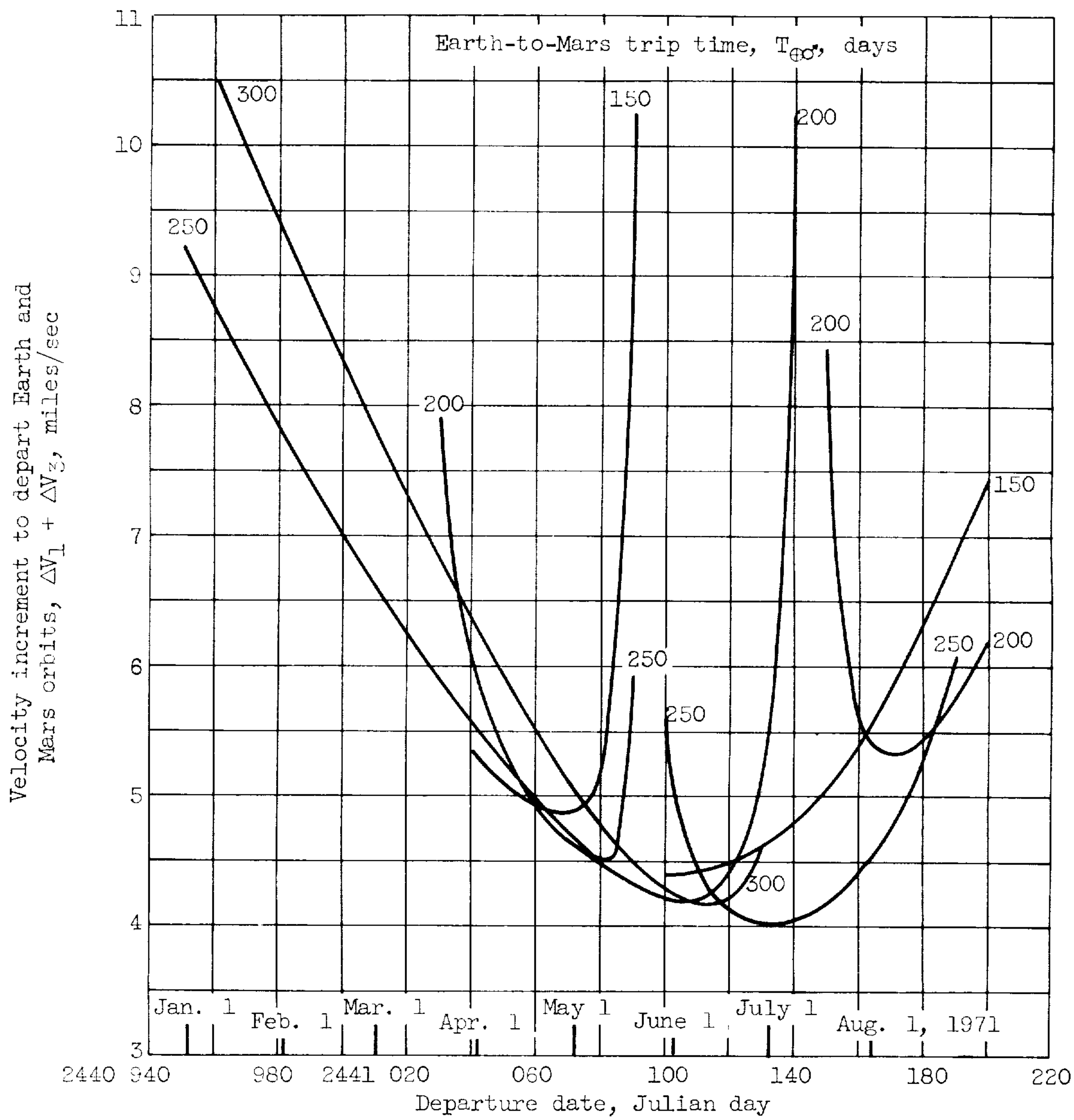
(b) Atmospheric braking at Earth.

Figure 1_. - Continued. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



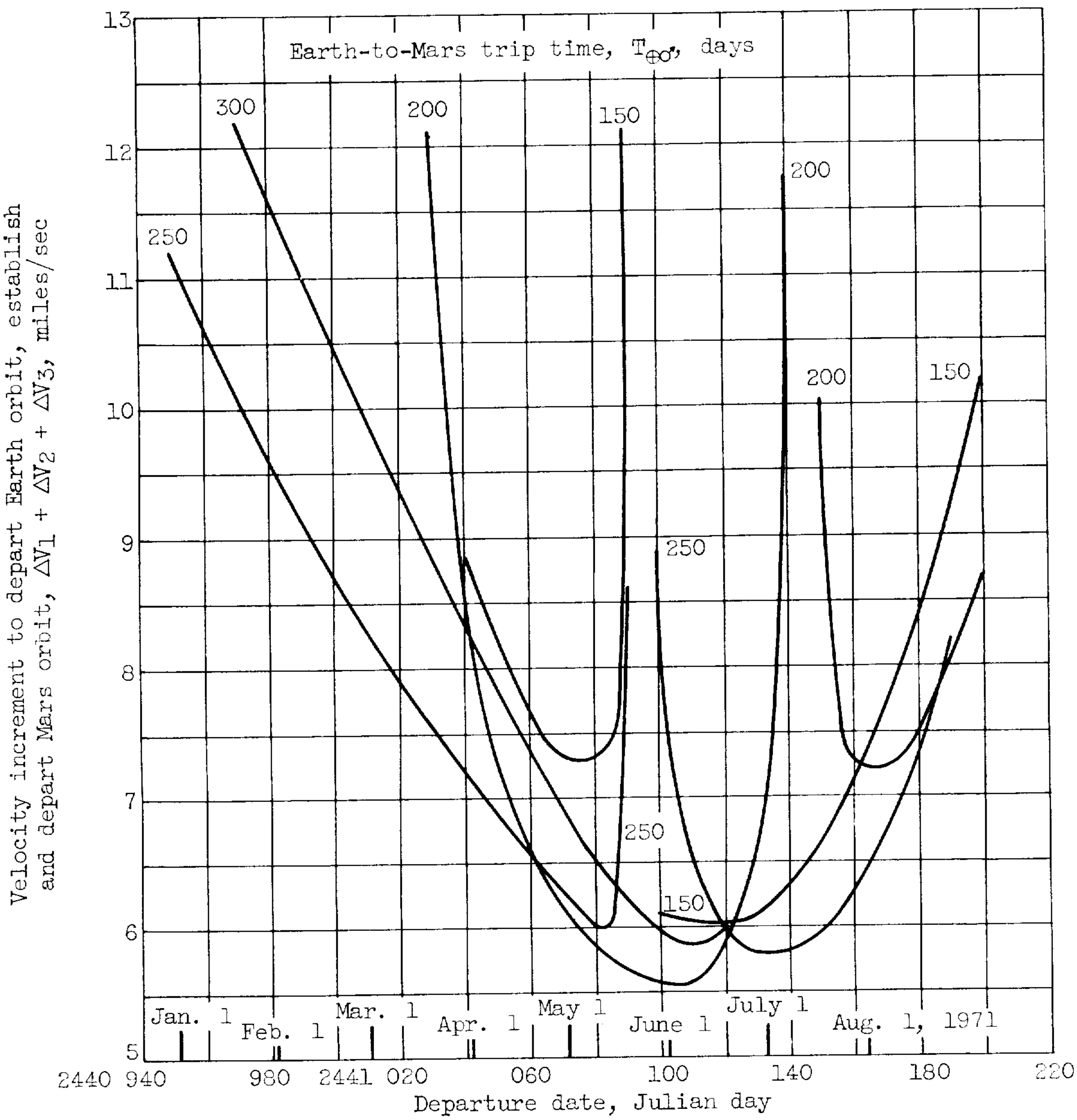
(c) All propulsive braking.

Figure 15. - Concluded. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



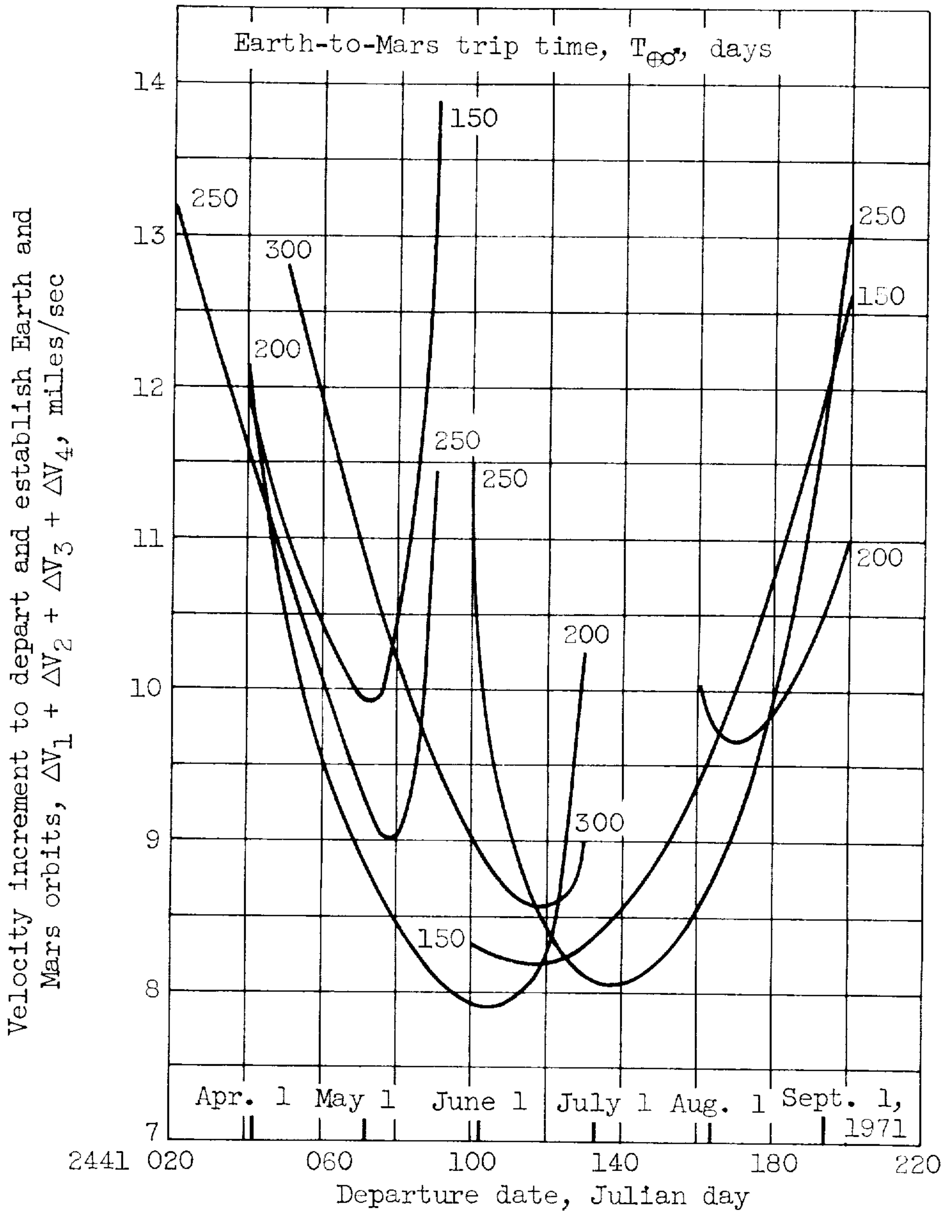
(a) Atmospheric braking at Mars and Earth.

Figure 16. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.



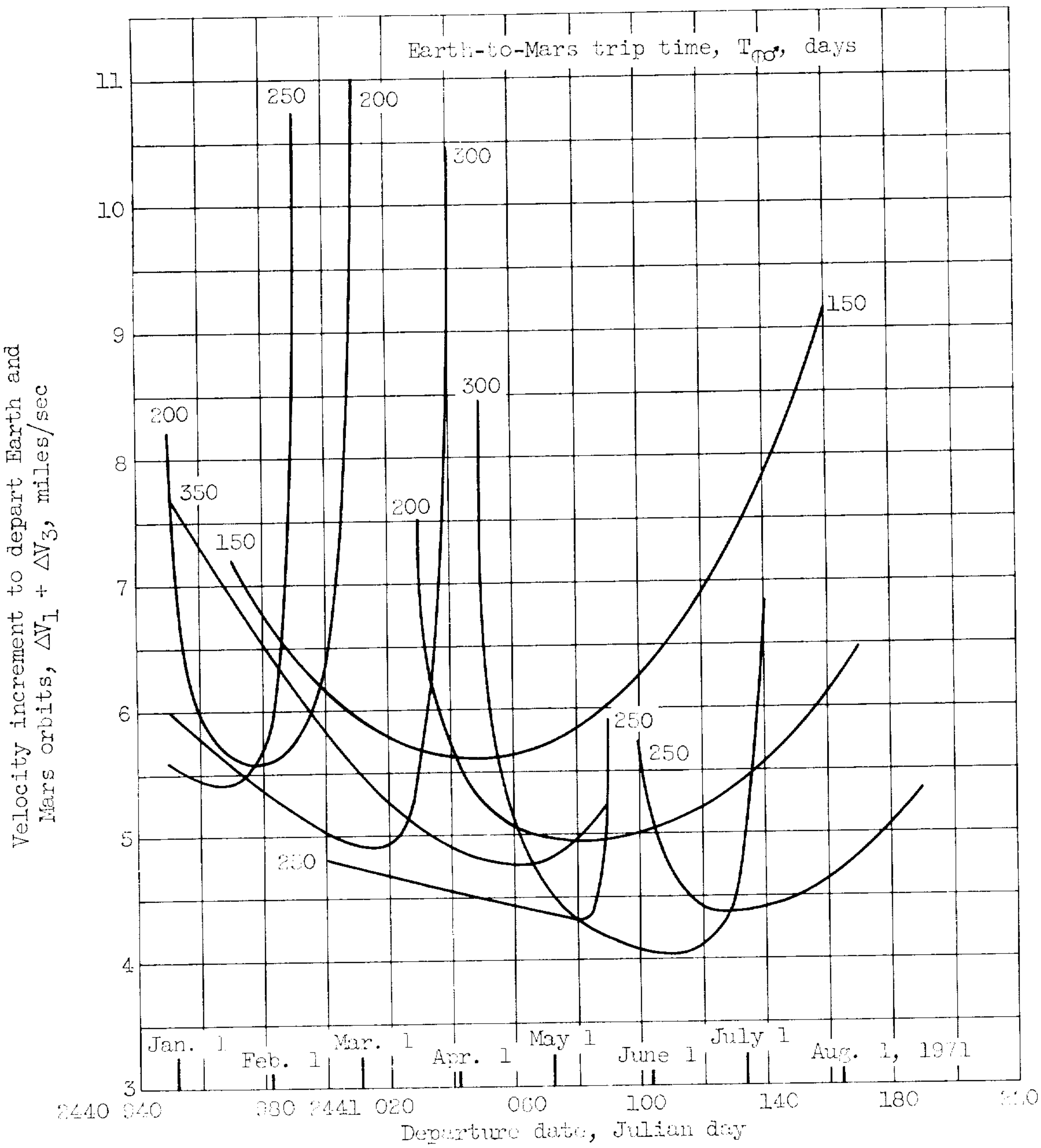
(b) Atmospheric braking at Earth.

Figure 16. - Continued. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.



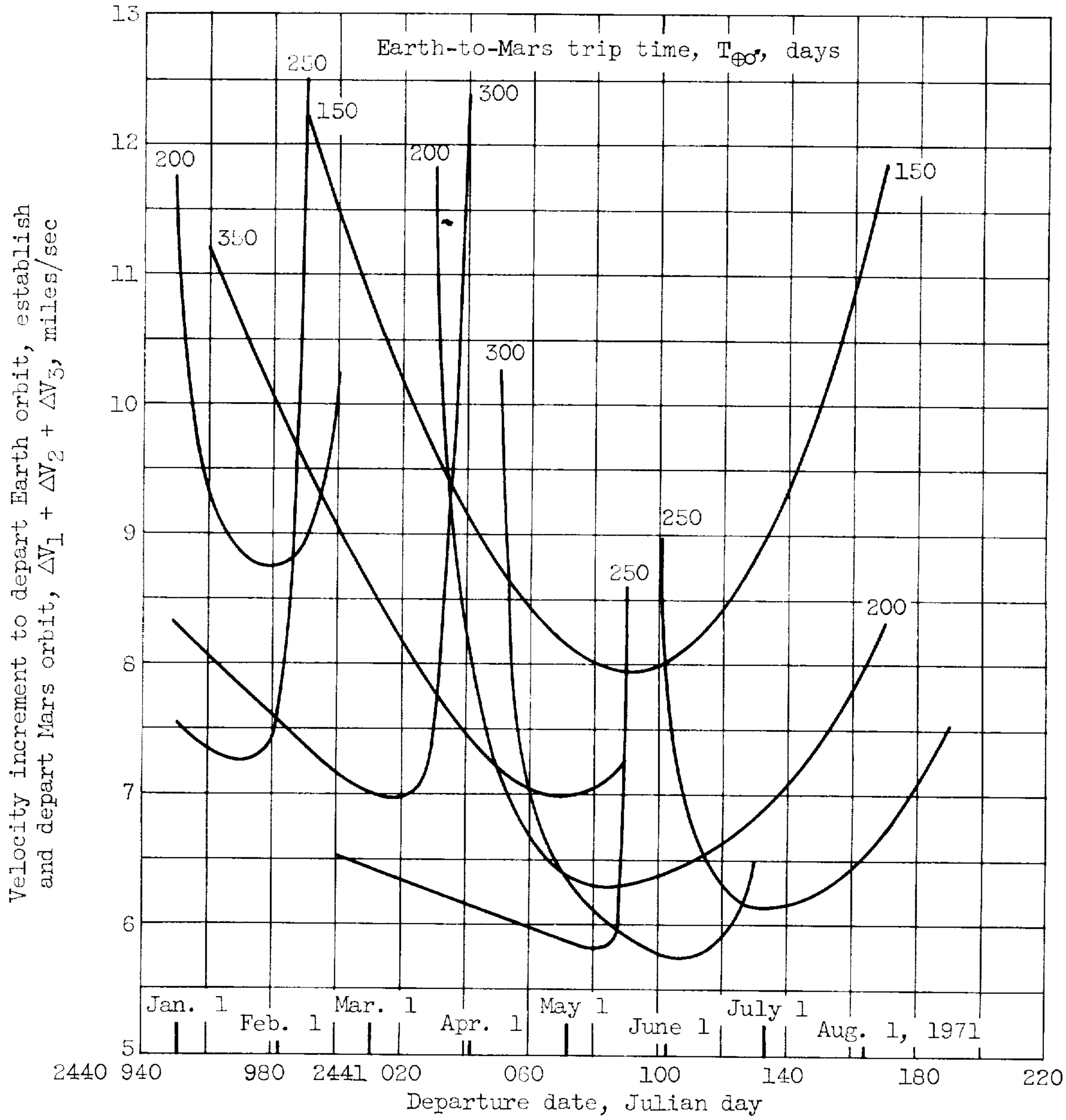
(c) All propulsive braking.

Figure 16. - Concluded. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.



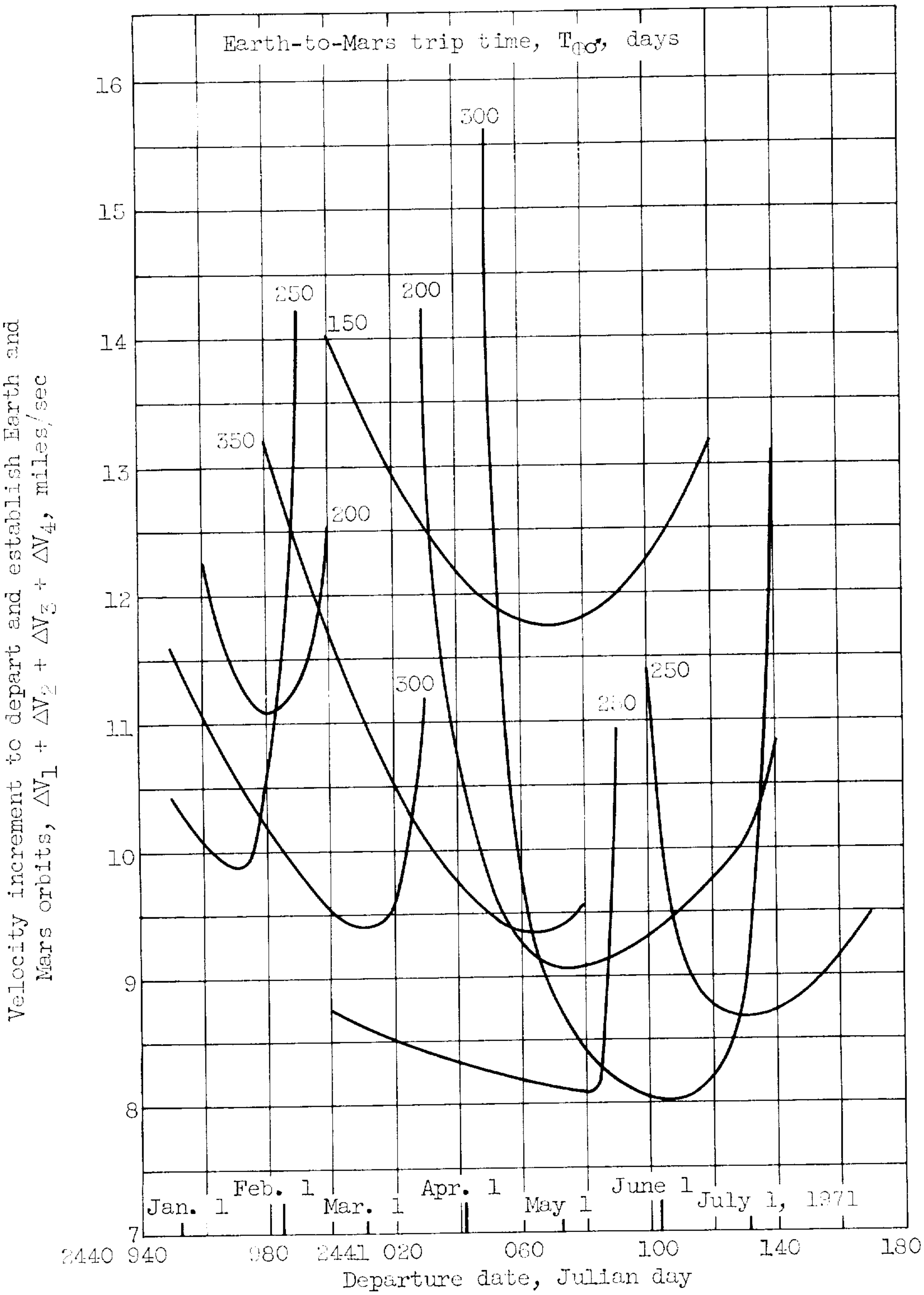
(a) Atmospheric braking at Mars and Earth.

Figure 17. - Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 450 days.



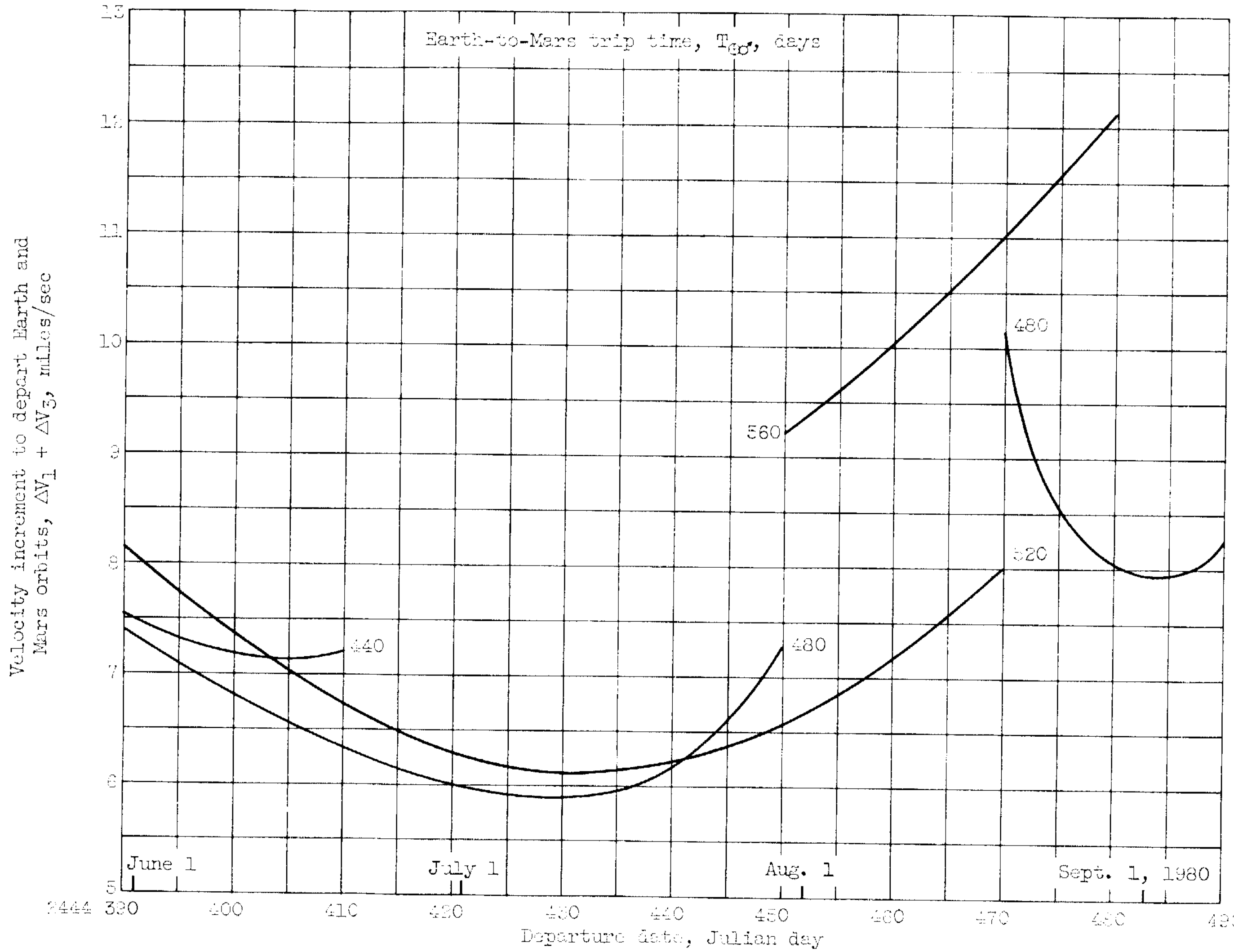
(b) Atmospheric braking at Earth.

Figure 17. - Continued. Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 450 days.



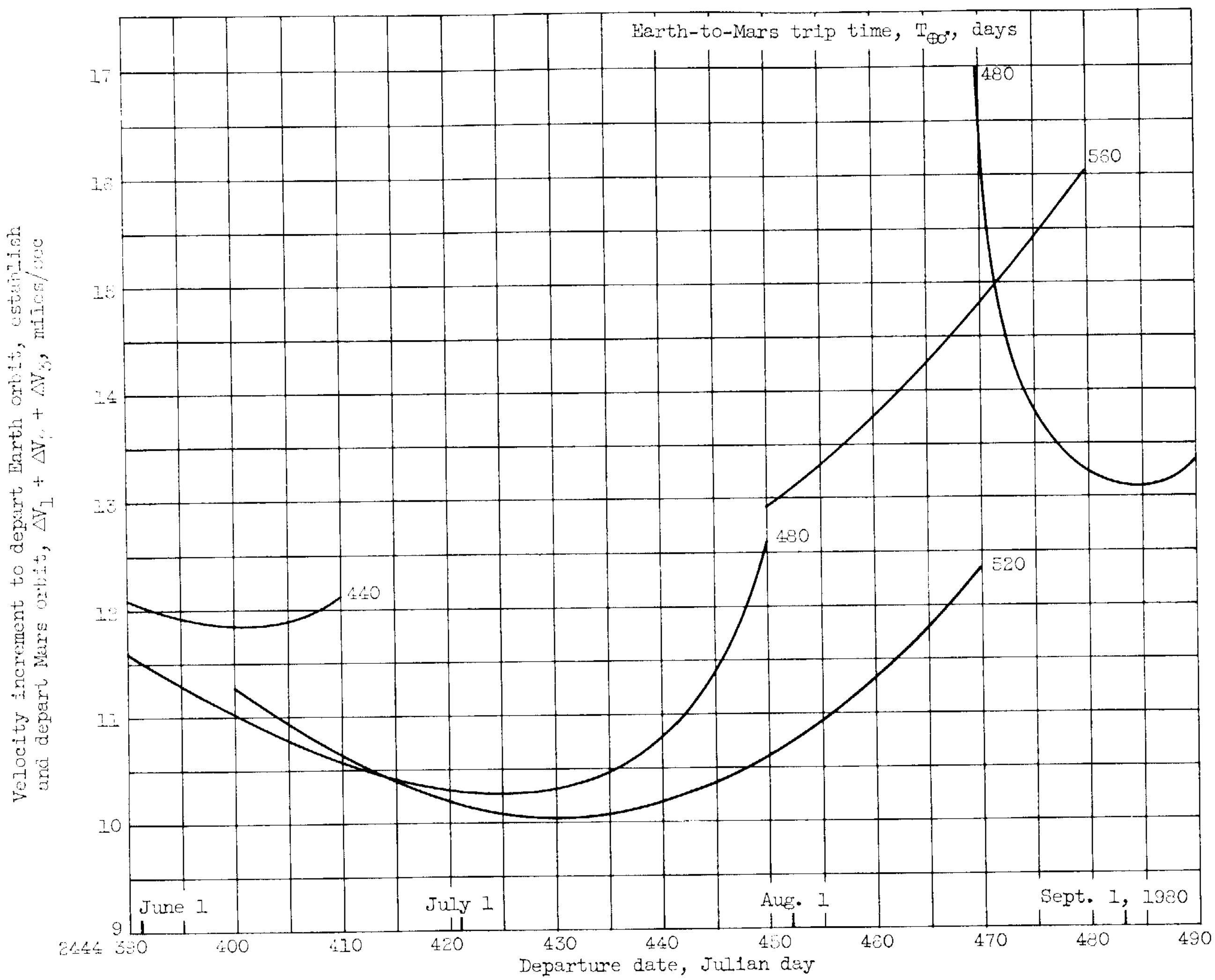
(c) All propulsive braking.

Figure 17. - Concluded. Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 450 days.



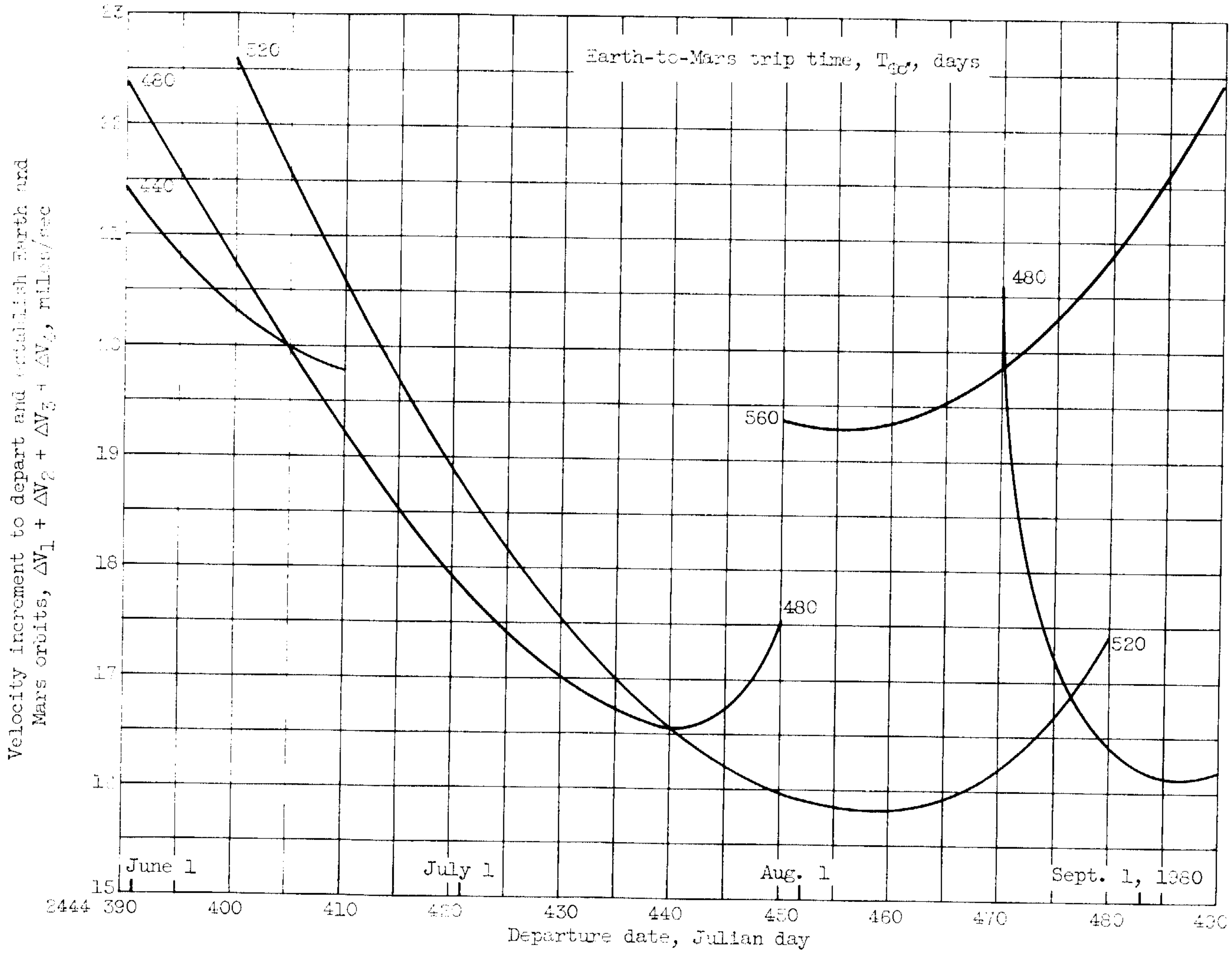
(a) Atmospheric braking at Mars and Earth.

Figure 14. - Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 0 day.



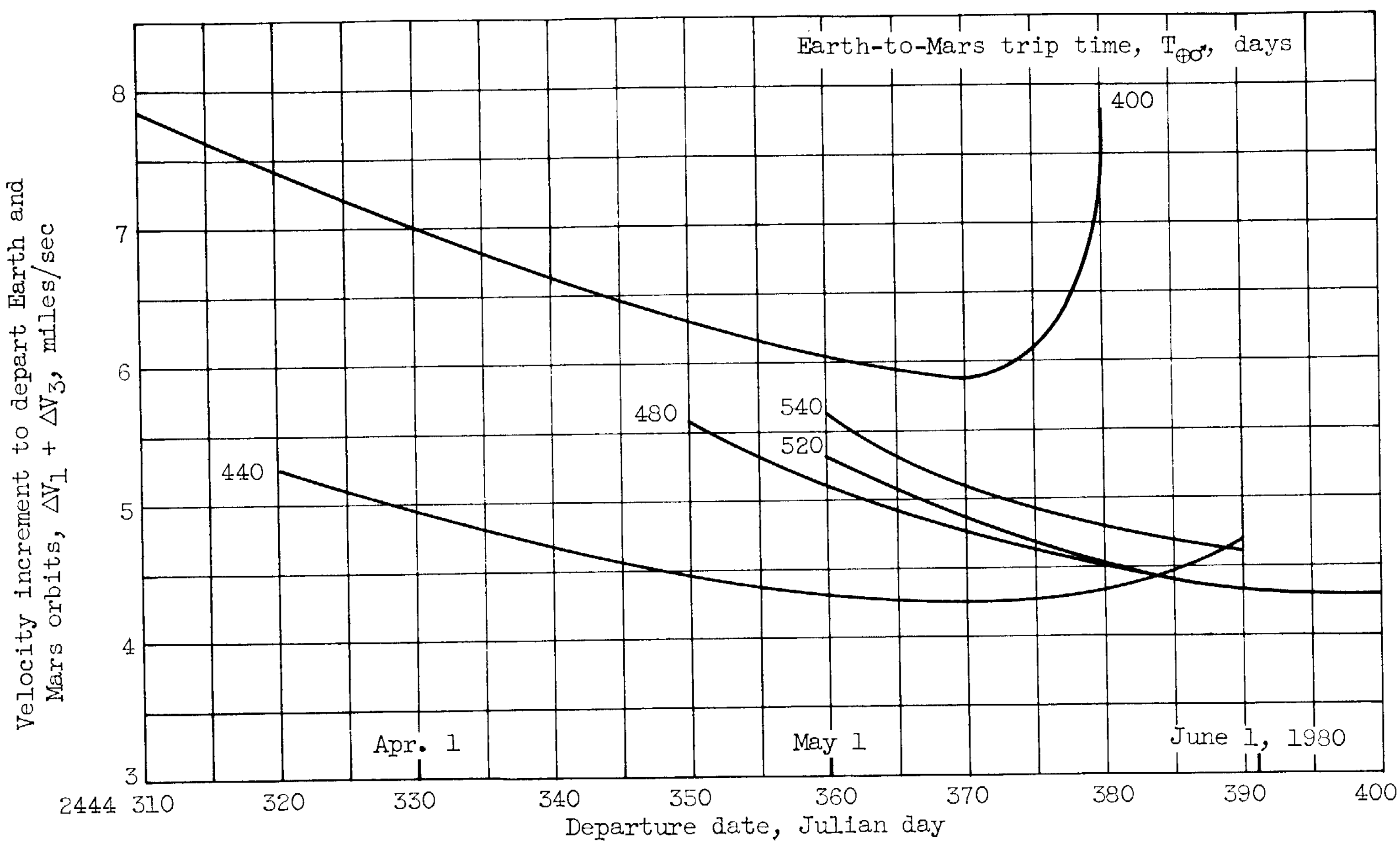
(b) Atmospheric braking at Earth.

Figure 18. - Continued. Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 0 day.



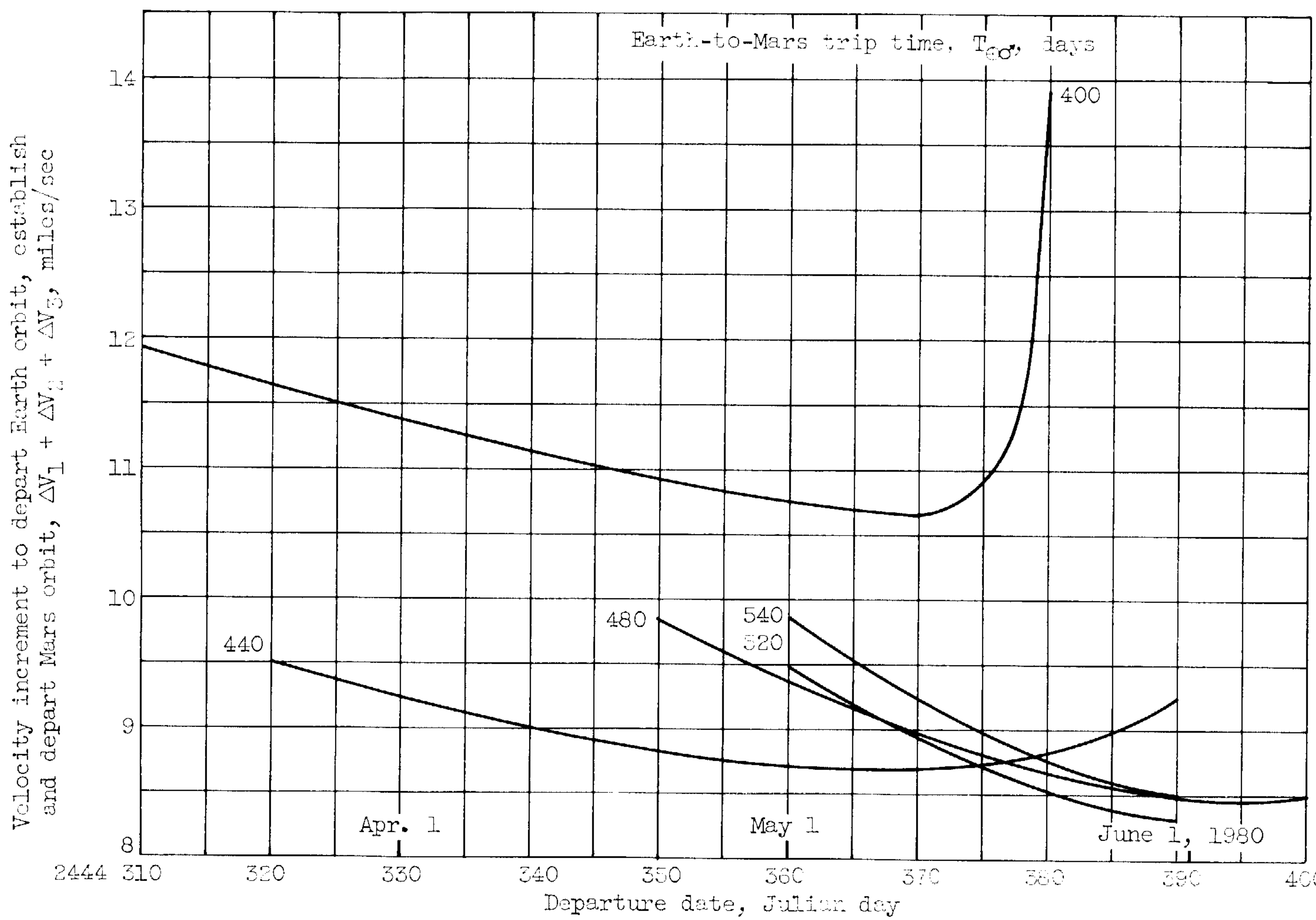
(c) All propulsive braking.

Figure 18. - Concluded. Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 0 day.



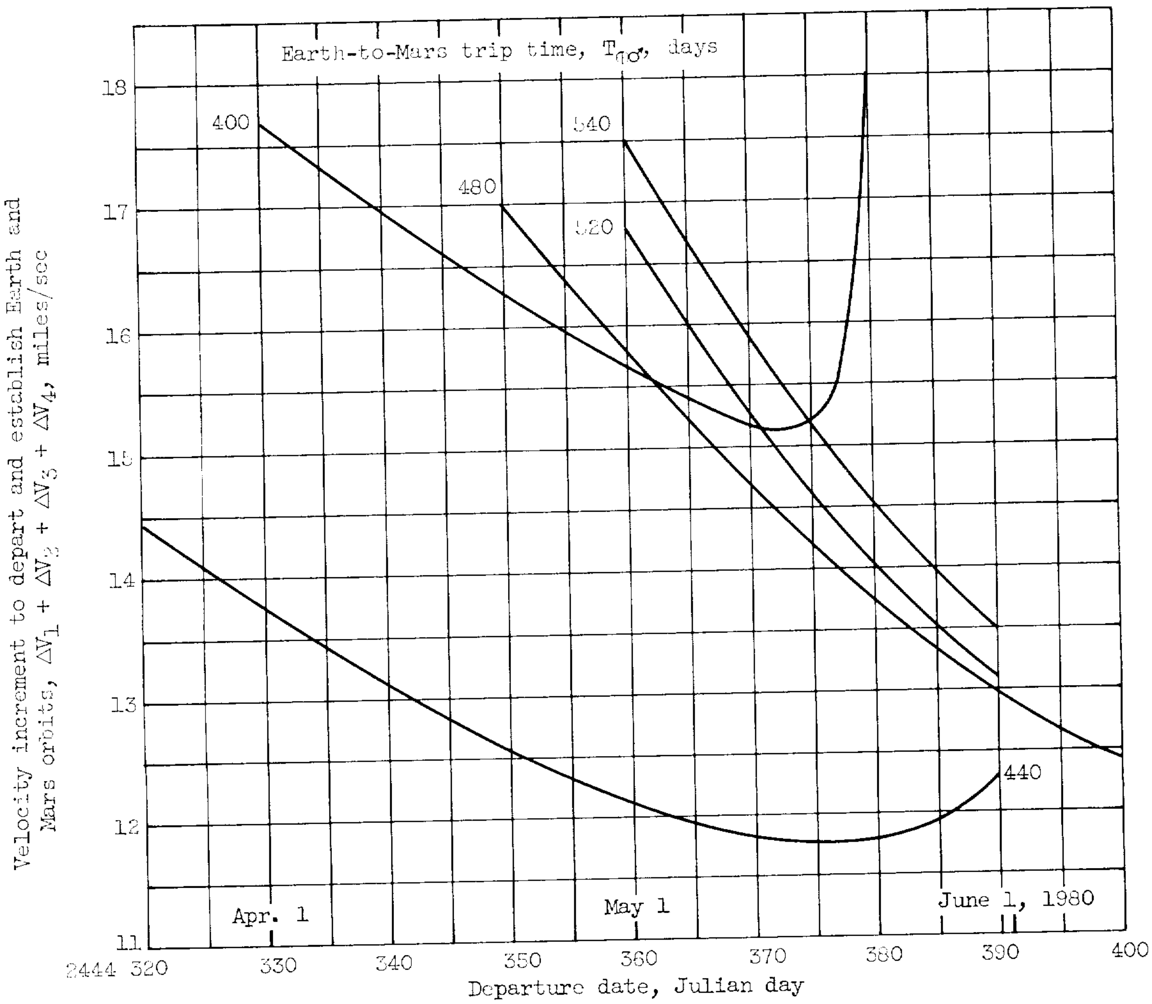
(a) Atmospheric braking at Mars and Earth.

Figure 19. - Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 0 day.



(b) Atmospheric braking at Earth.

Figure 19. - Continued. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 0 day.



(c) All propulsive braking.

Figure 19. - Concluded. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 0 day.

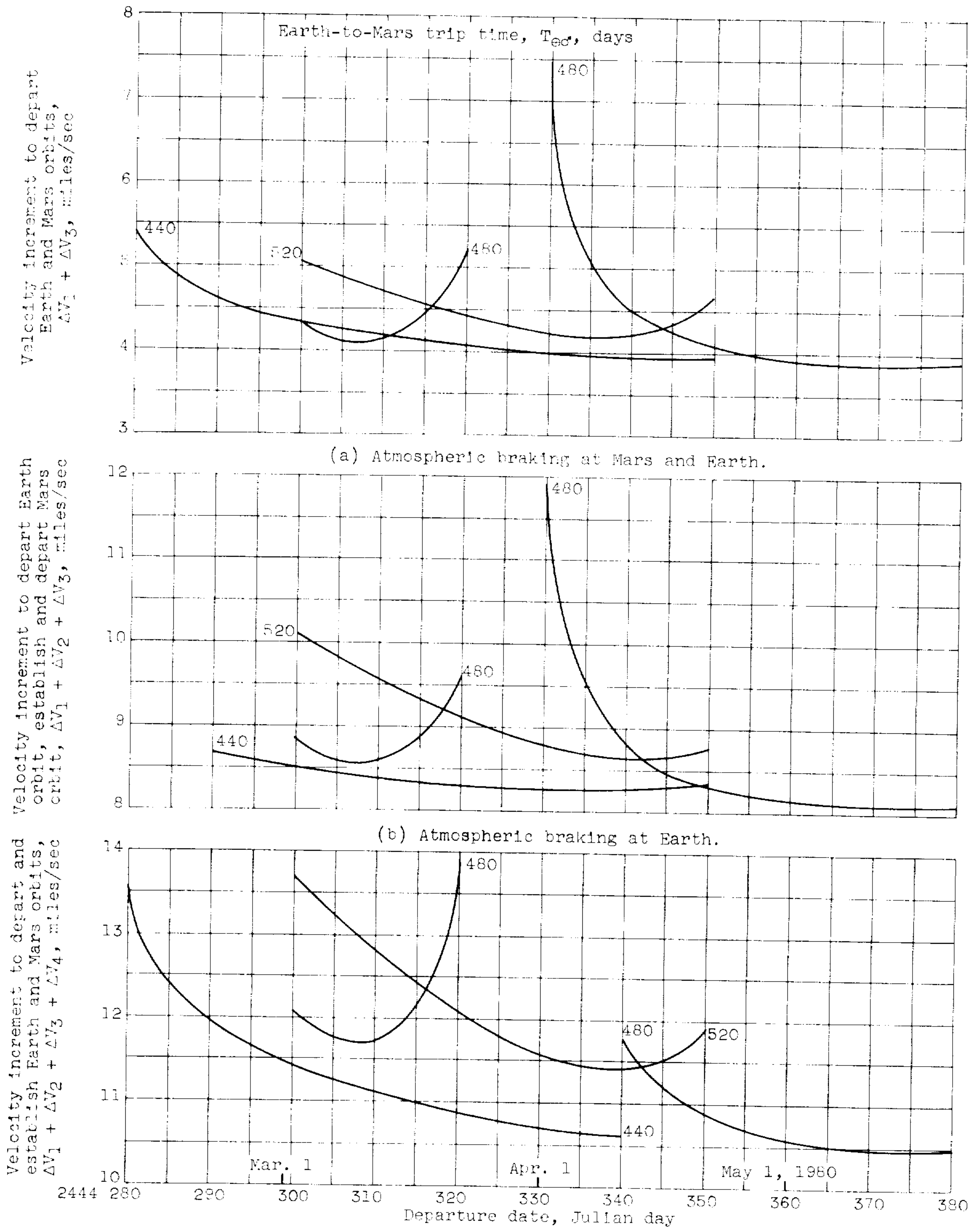
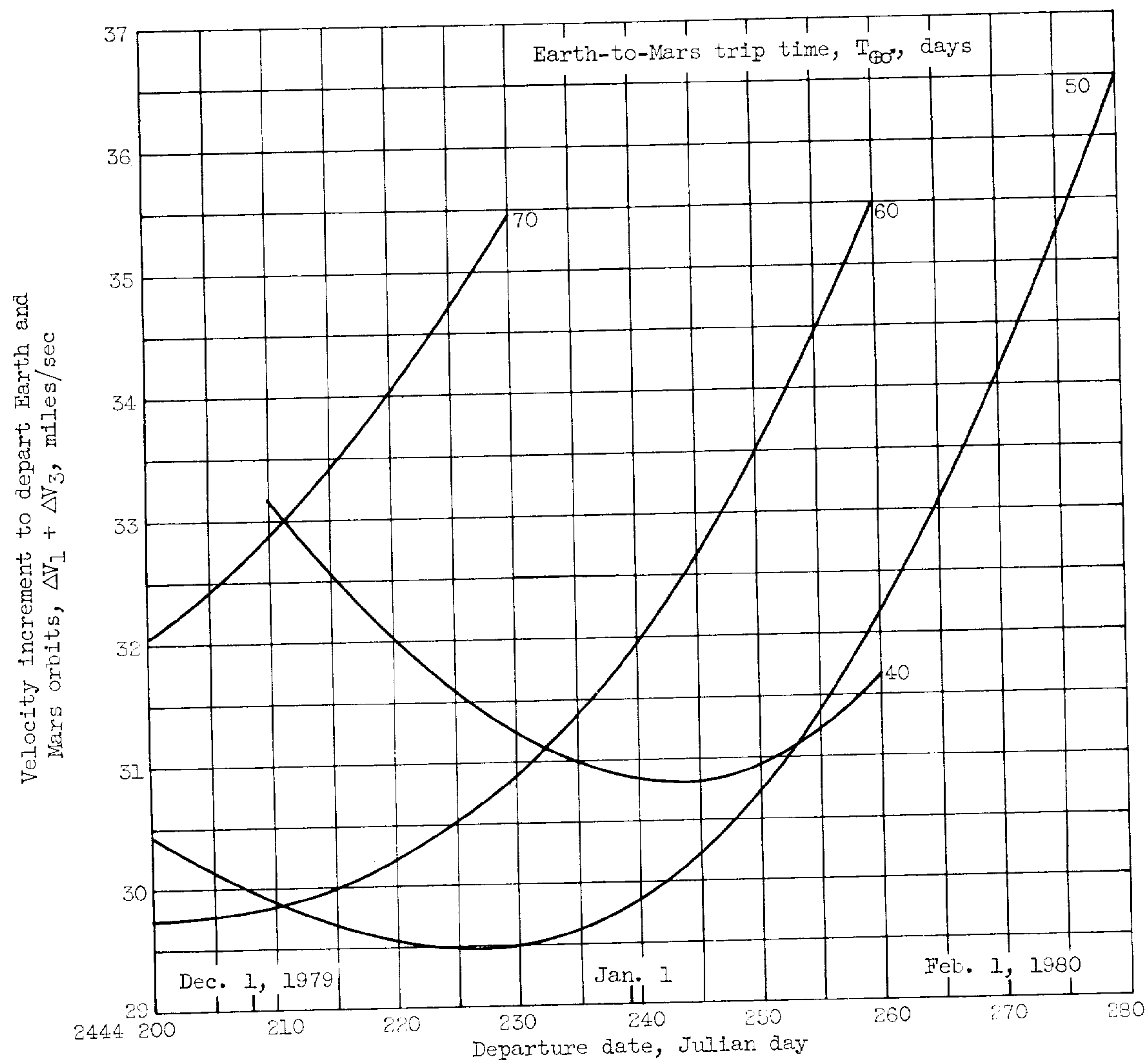
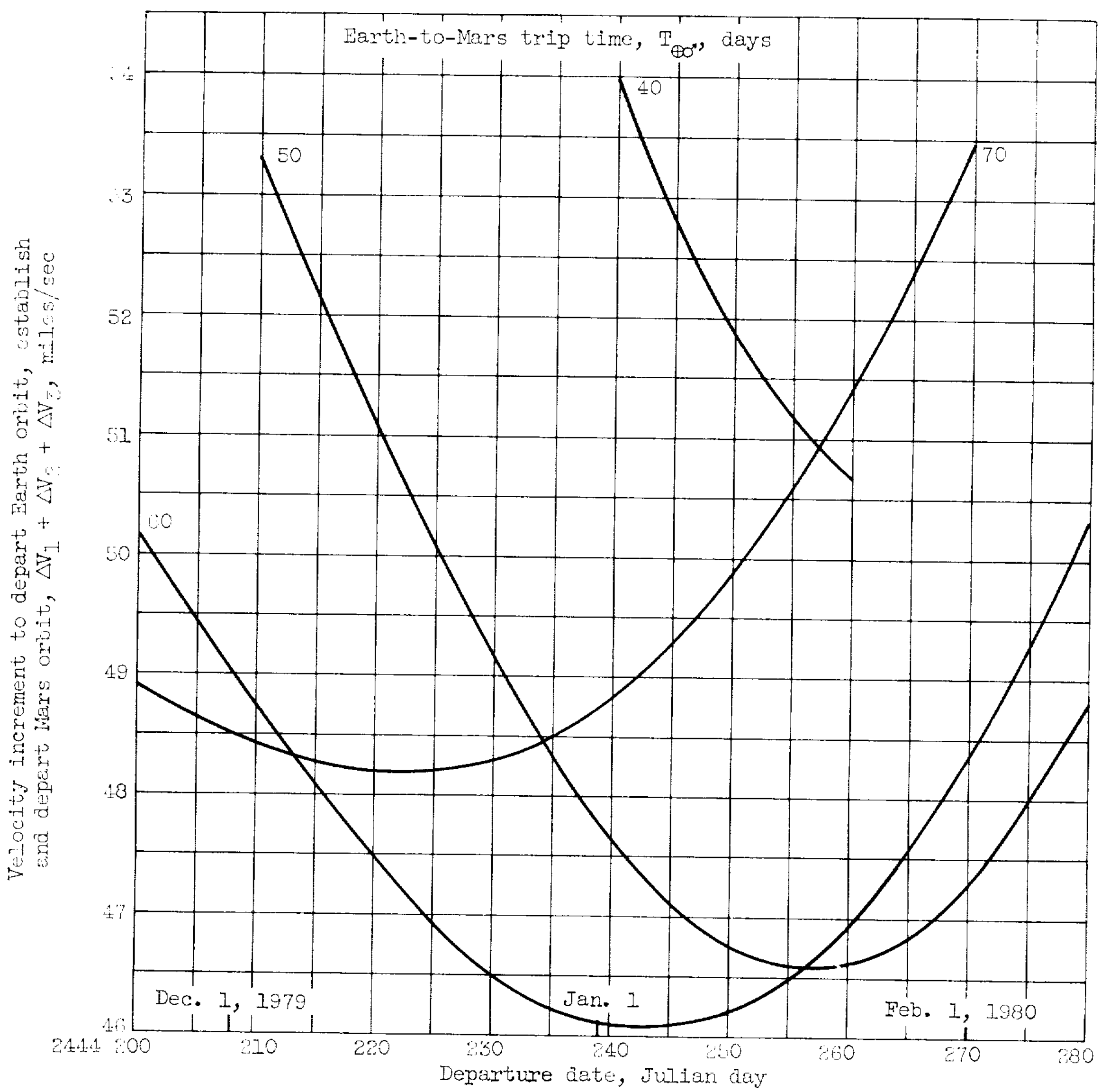


Figure 20. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 0 day.



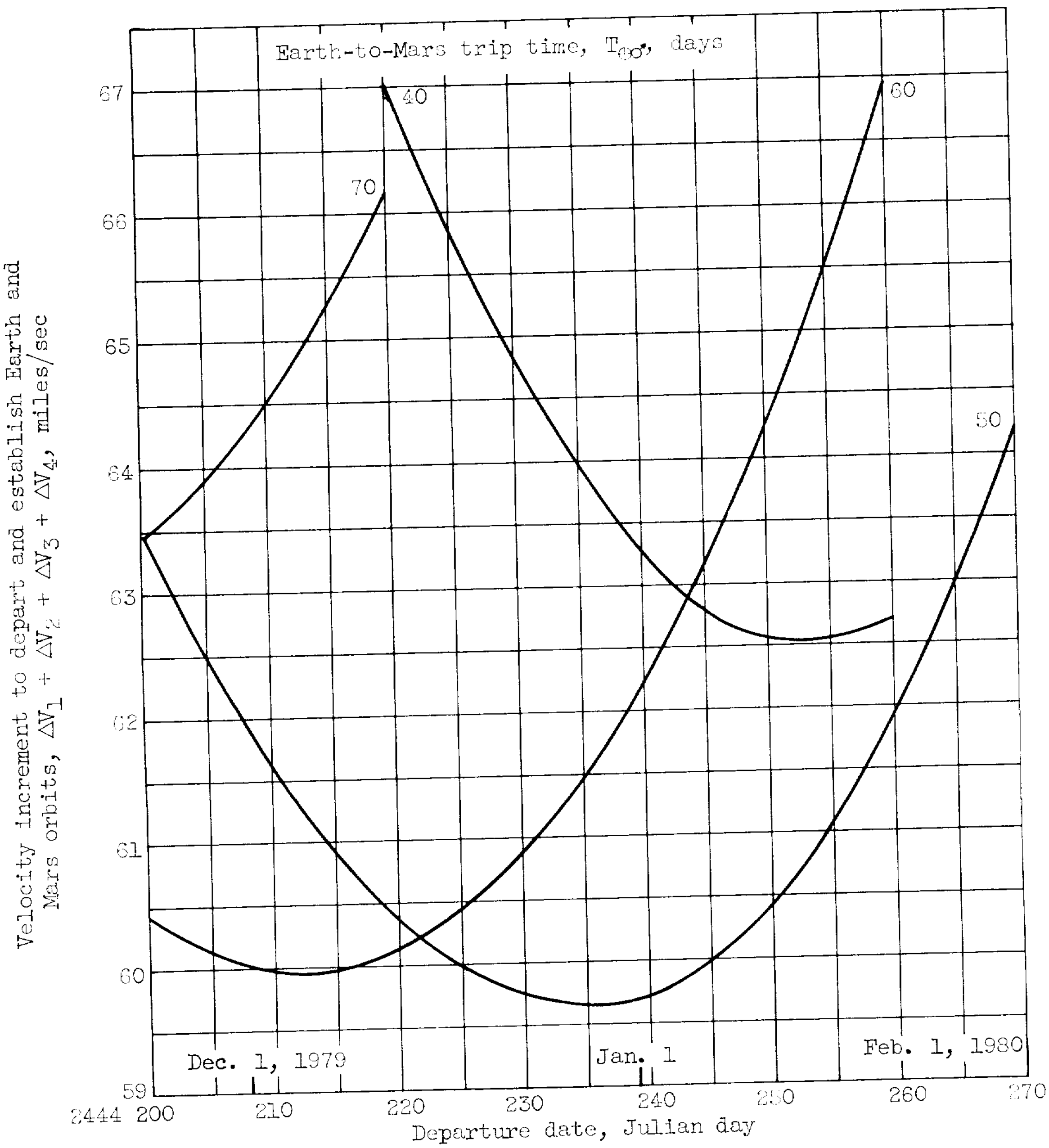
(a) Atmospheric braking at Mars and Earth.

Figure 21. - Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



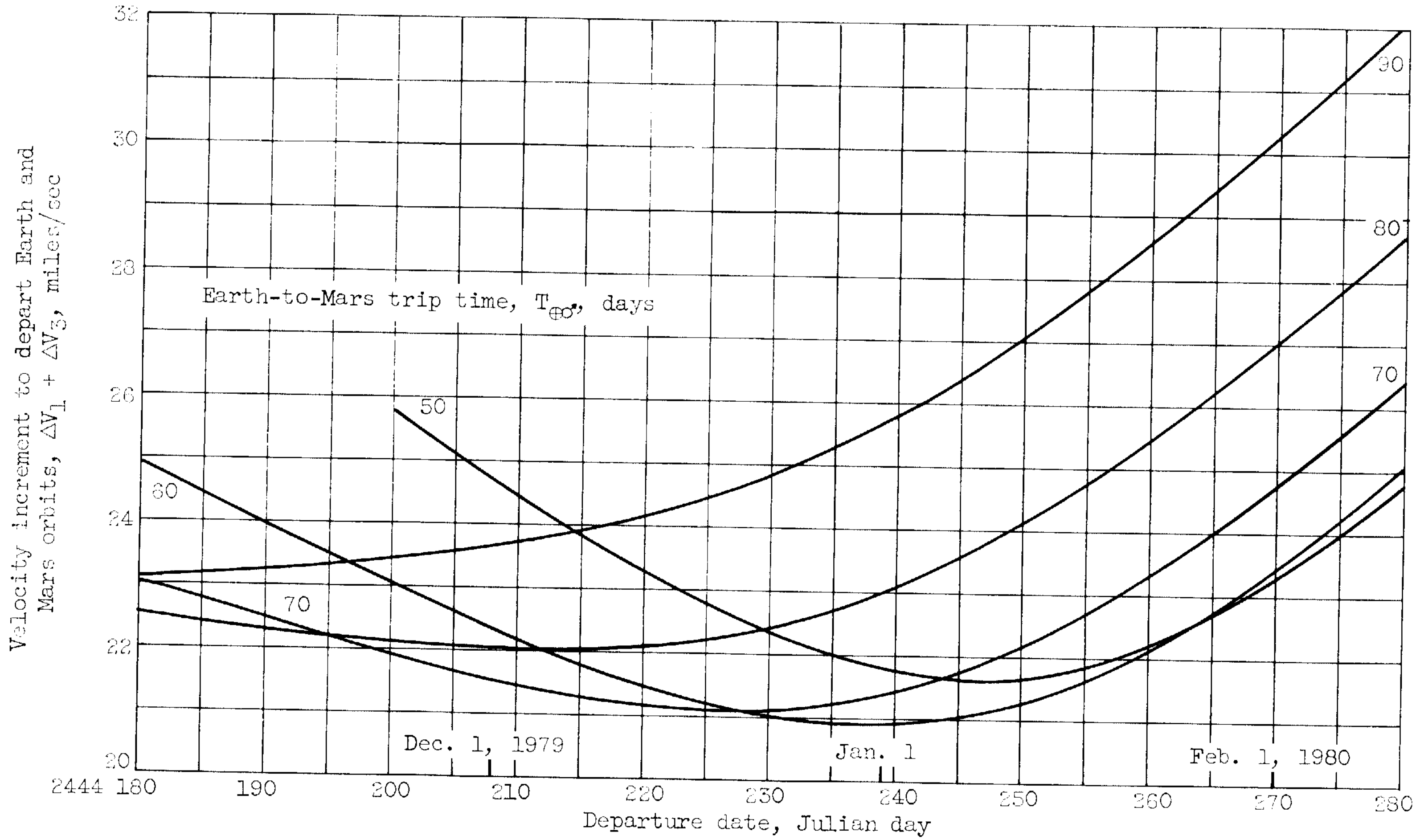
(b) Atmospheric braking at Earth.

Figure 21. - Continued. Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



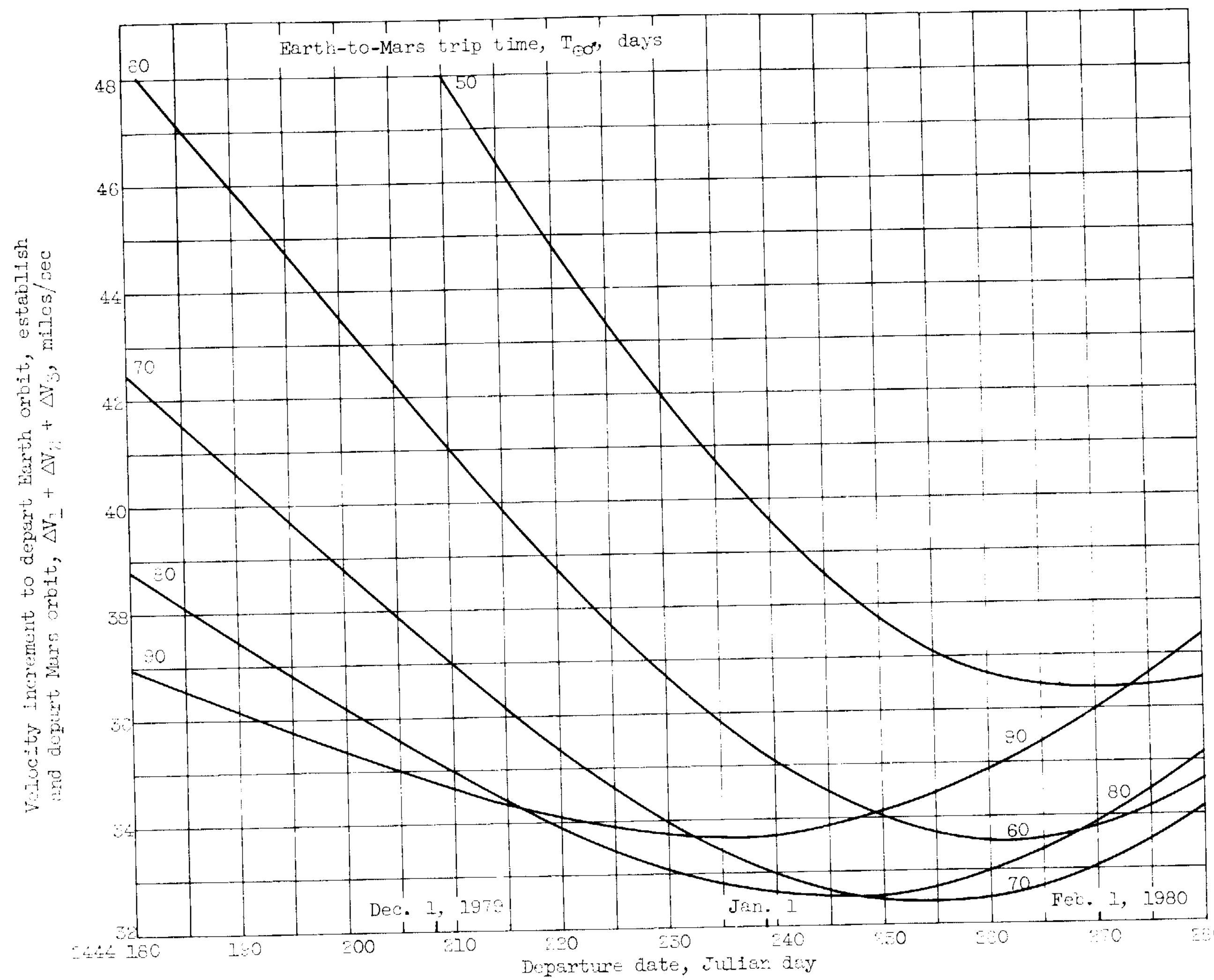
(c) All propulsive braking.

Figure 21. - Concluded. Velocity increments for 150-day round trip to Mars. Wait time in Mars orbit, 40 days.



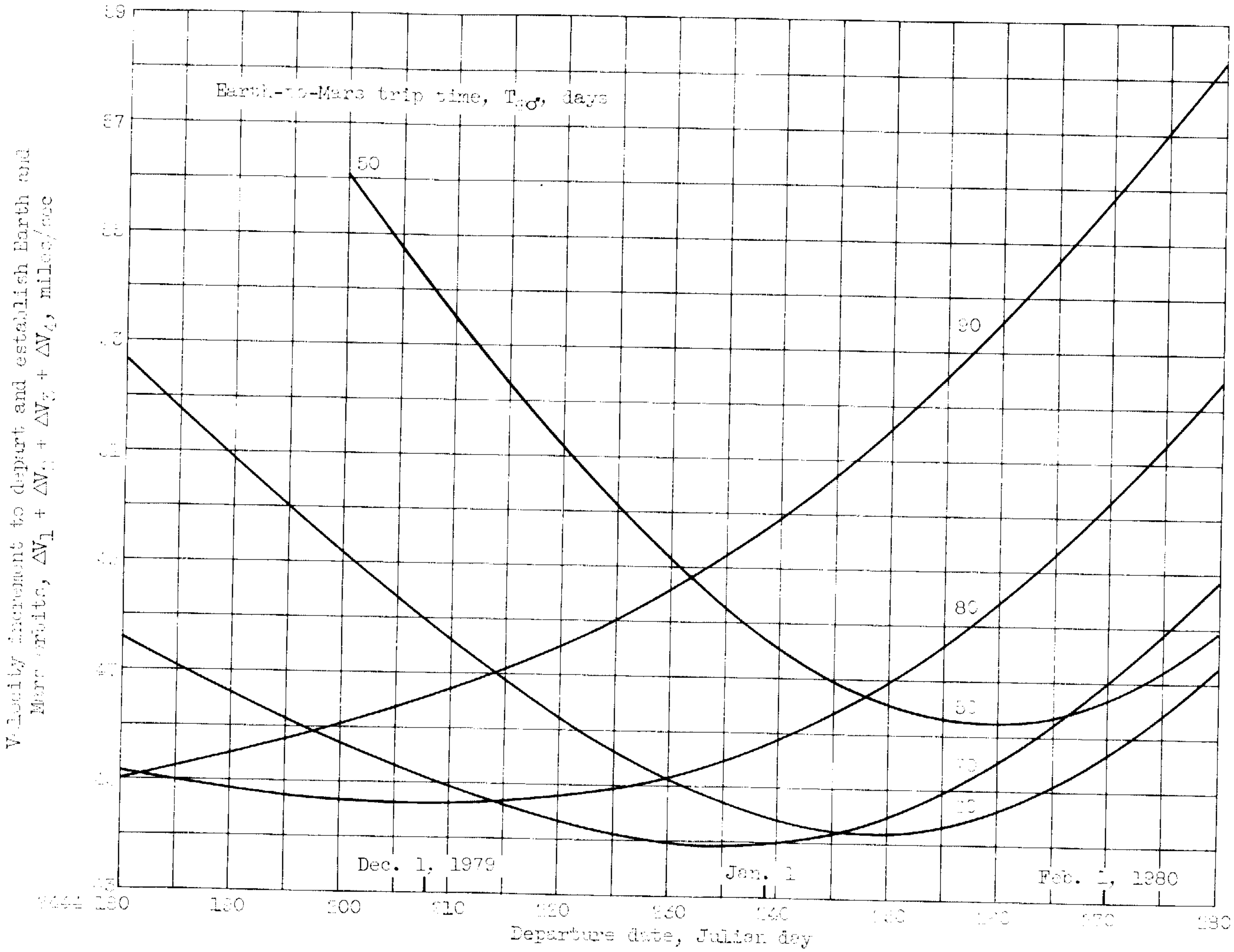
(a) Atmospheric braking at Mars and Earth.

Figure 22. - Velocity increments for 200-day round trip to Mars. Wait time in Mars orbit, 40 days.



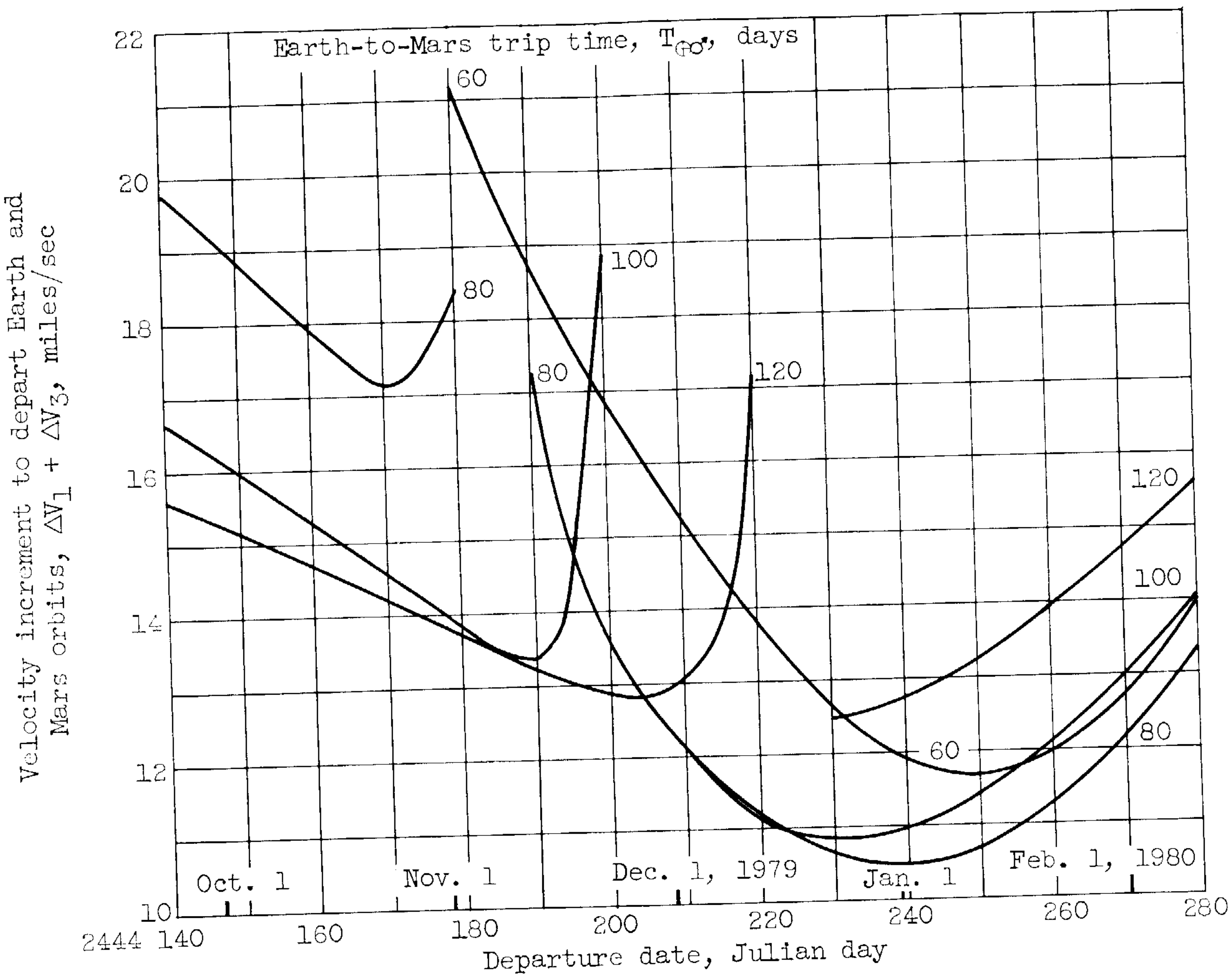
(b) Atmospheric braking at Earth.

Figure [illegible]. - Continued. Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



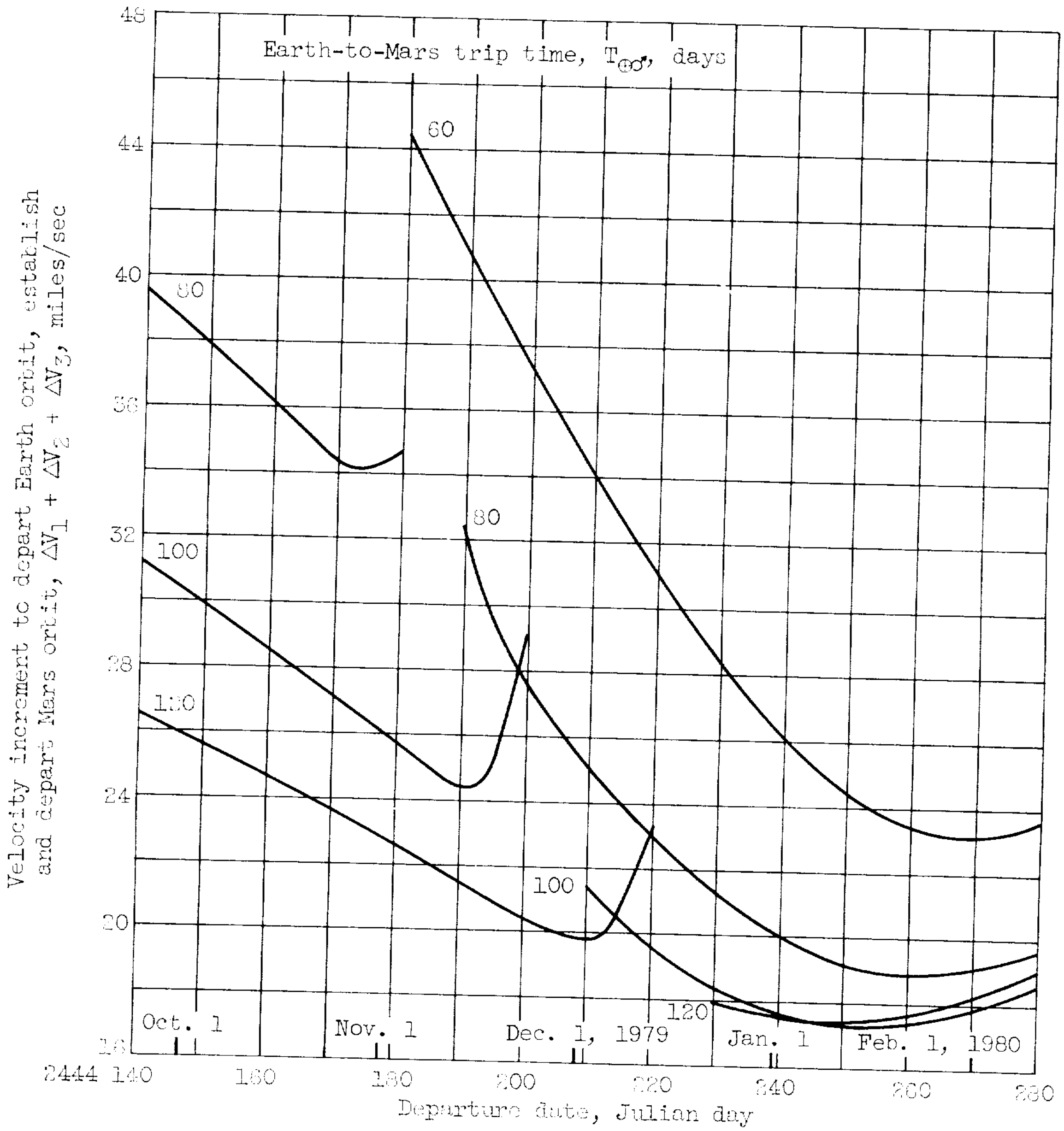
(c) All propulsive braking.

Figure [illegible]. - Concluded. Velocity increments for [illegible]00-day round trip to Mars. Wait time in Mars orbit, 40 days.



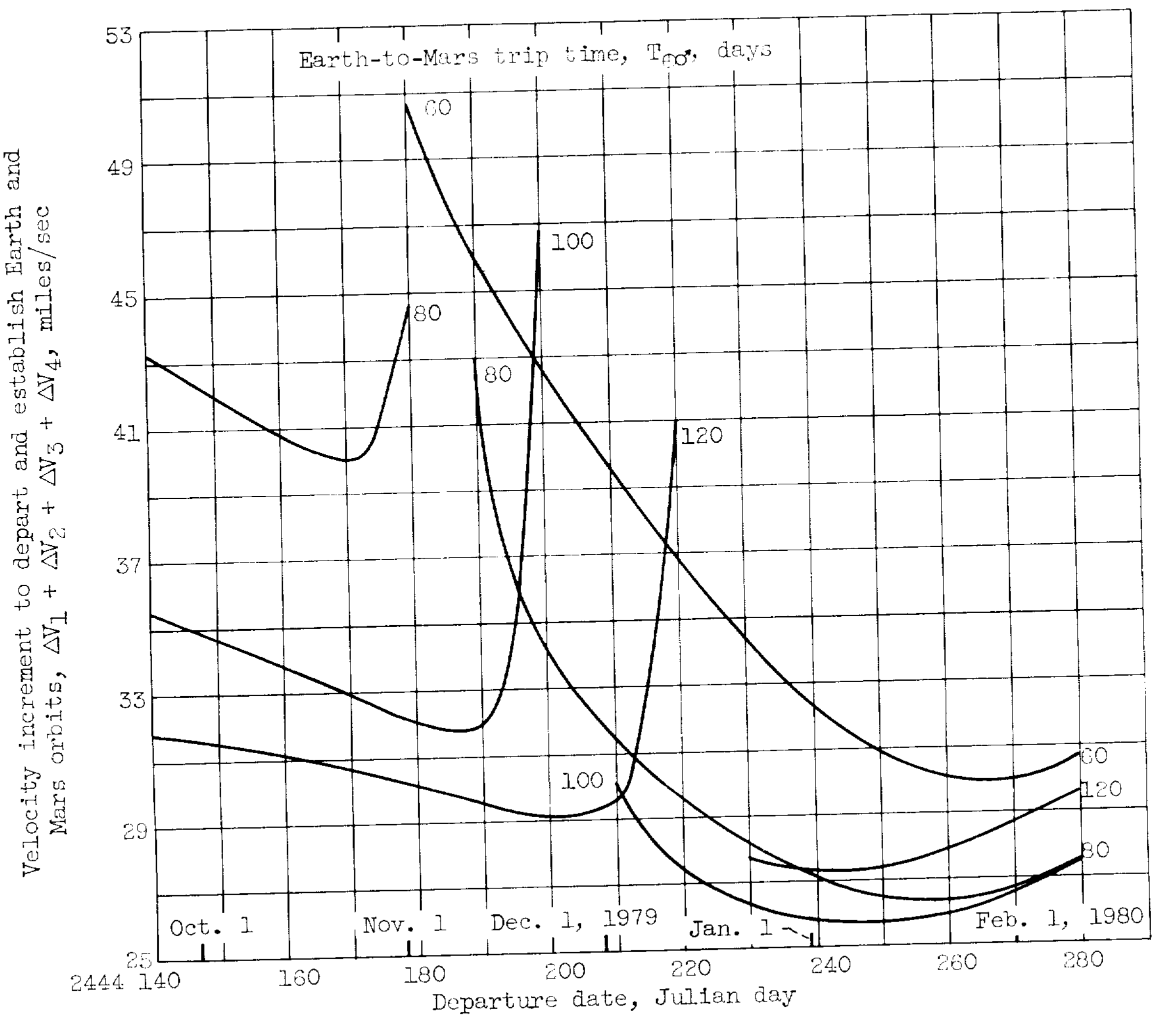
(a) Atmospheric braking at Mars and Earth.

Figure 23. - Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



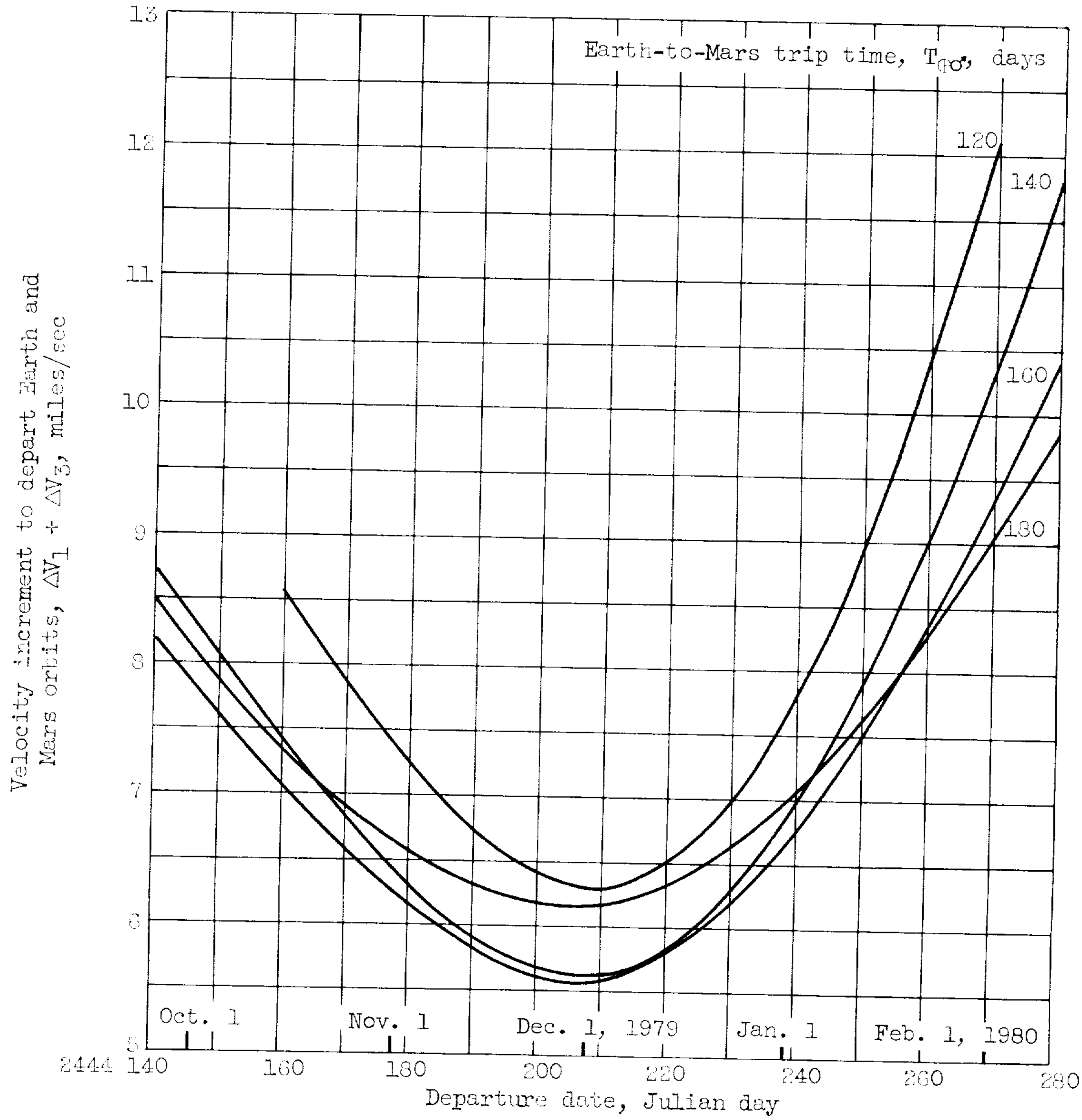
(b) Atmospheric braking at Earth.

Figure 23. - Continued. Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



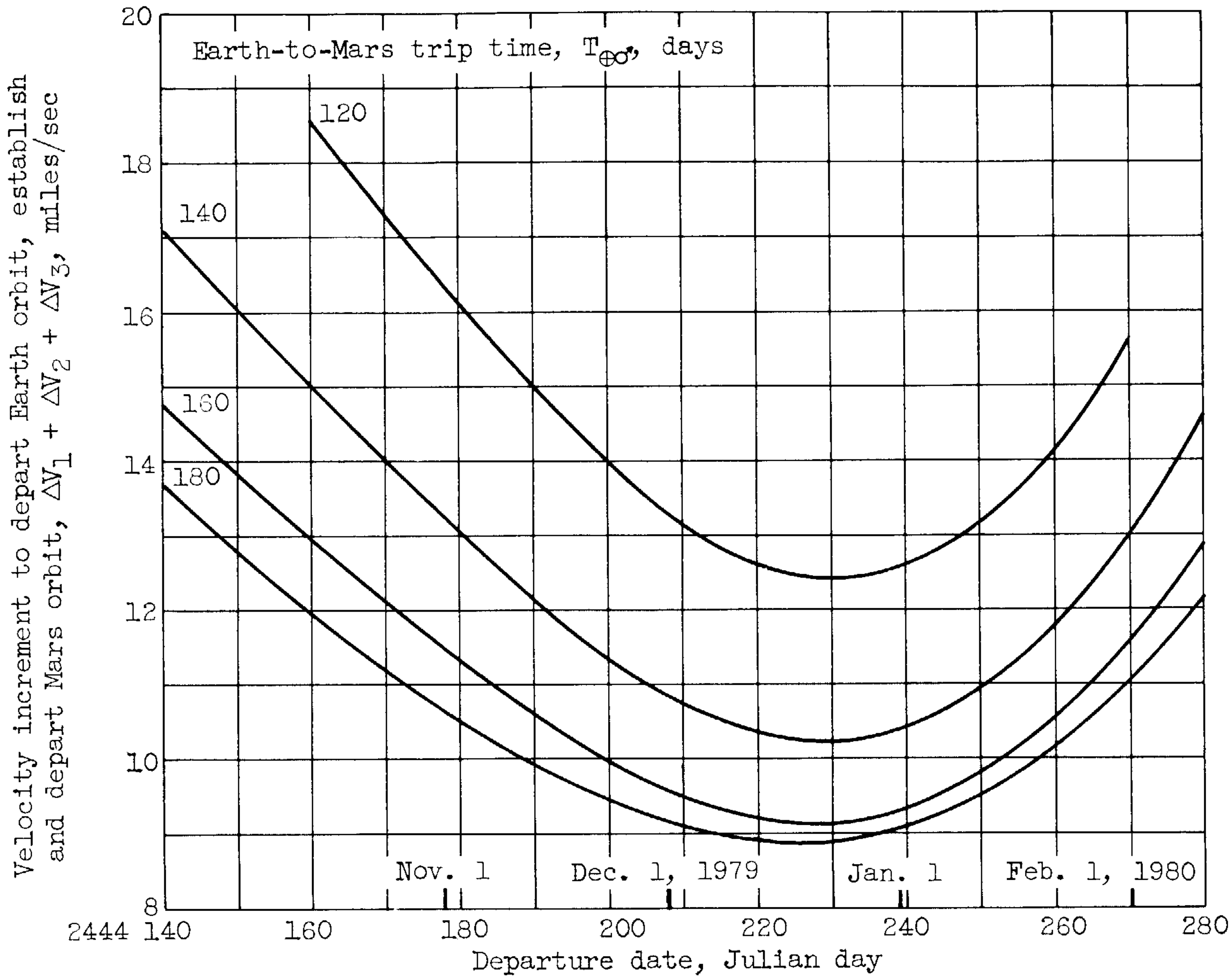
(c) All propulsive braking.

Figure 23. - Concluded. Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



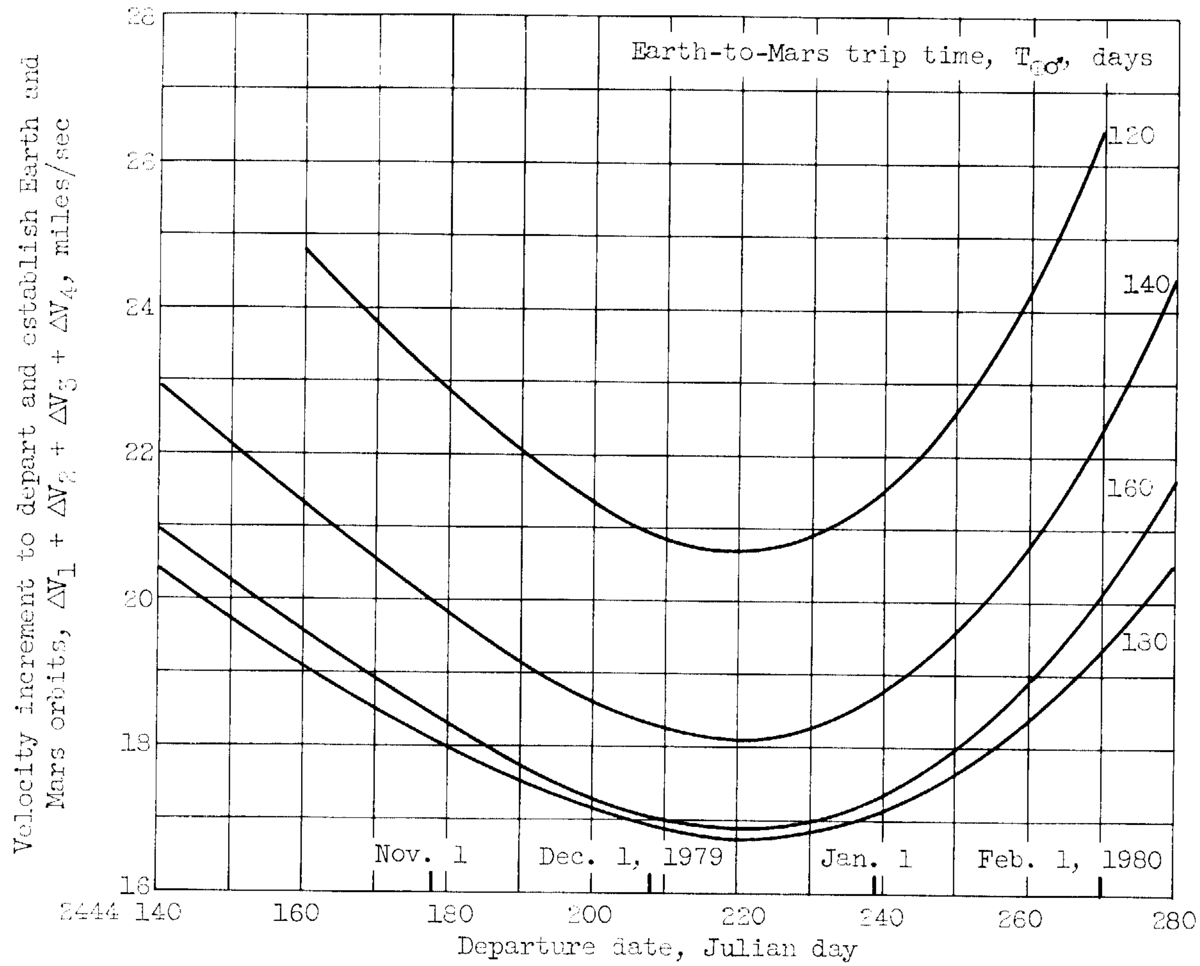
(a) Atmospheric braking at Mars and Earth.

Figure 24. - Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



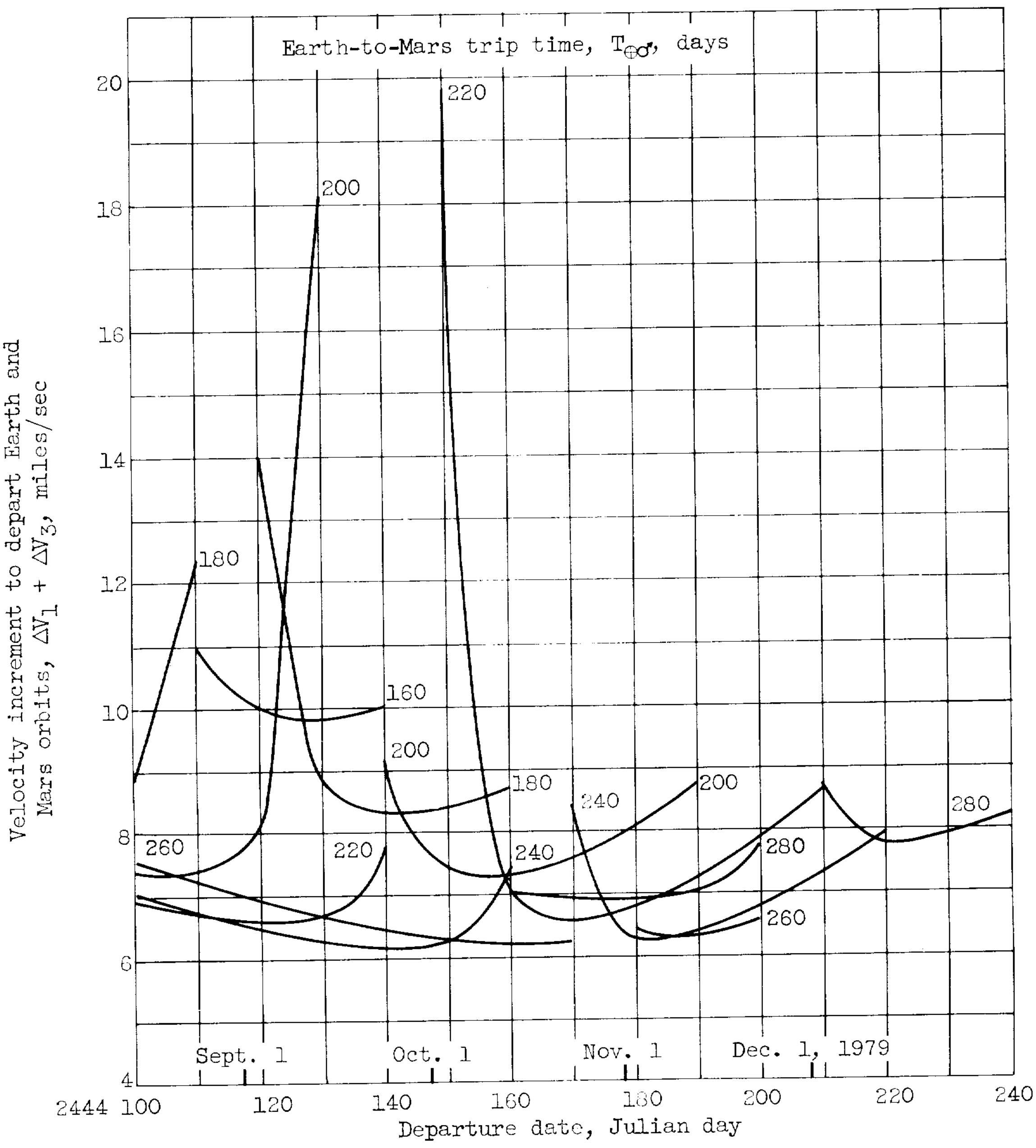
(b) Atmospheric braking at Earth.

Figure 24. - Continued. Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



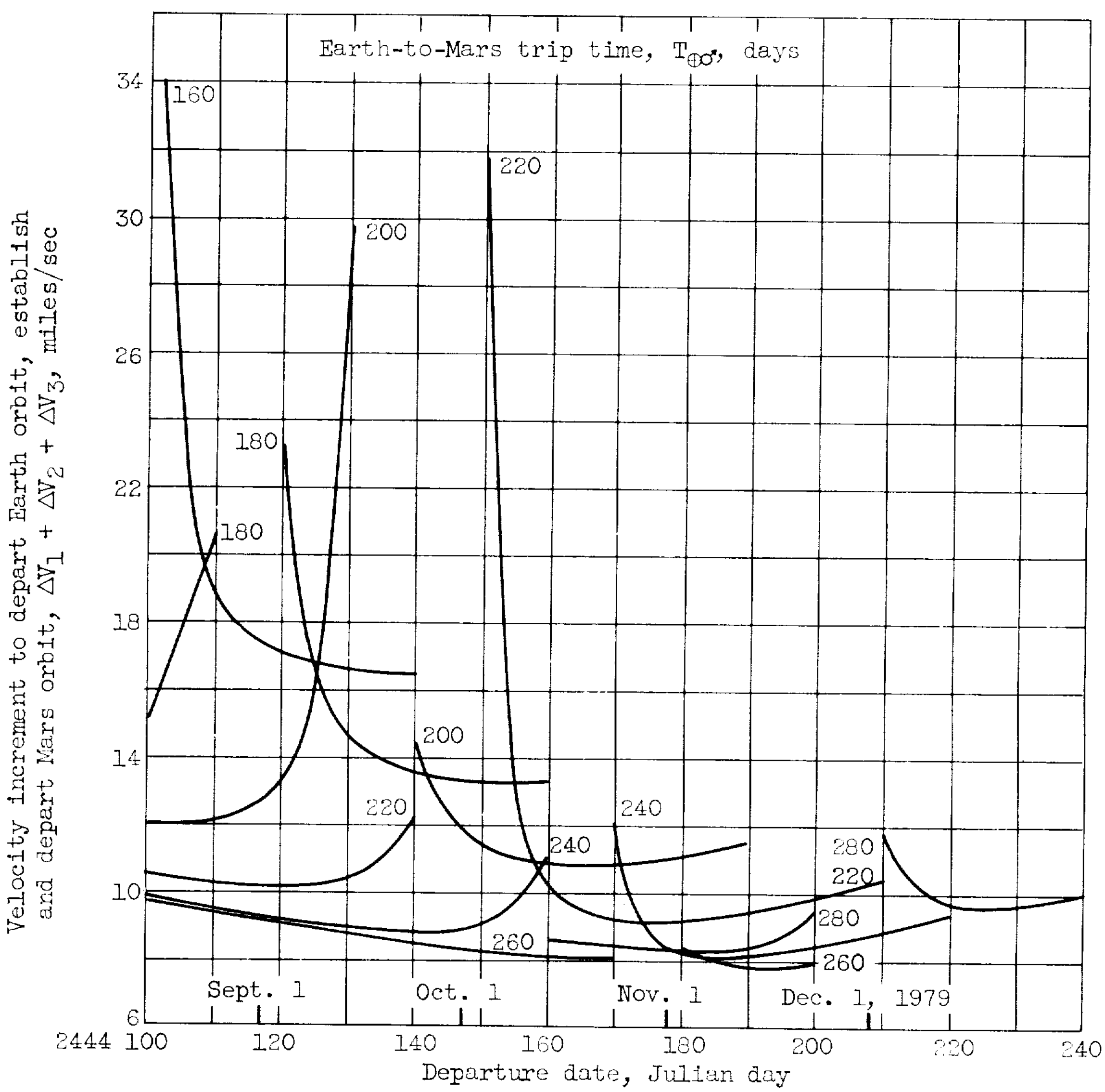
(c) All propulsive braking.

Figure 24. - Concluded. Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 40 days.



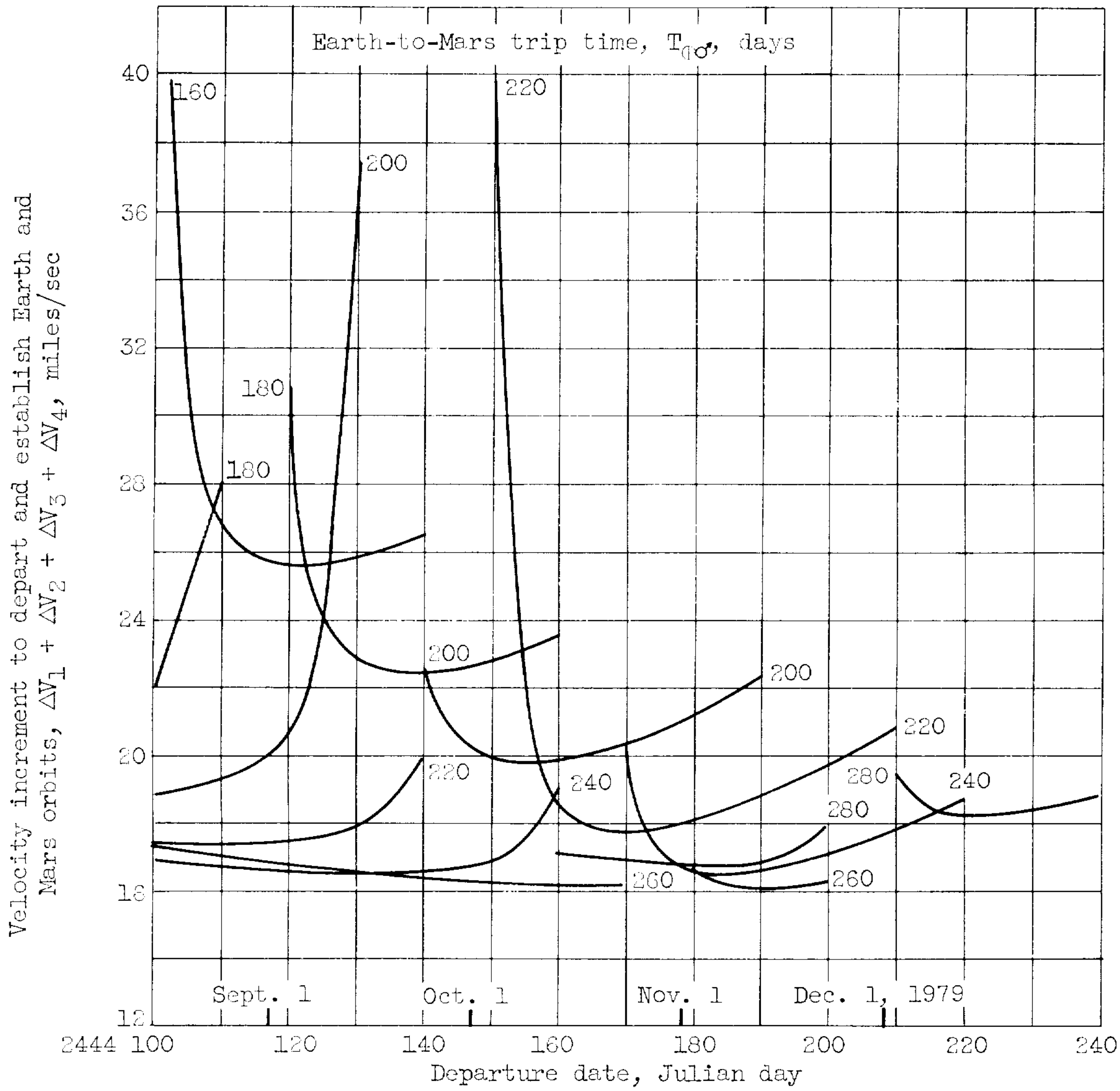
(a) Atmospheric braking at Mars and Earth.

Figure 25. - Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



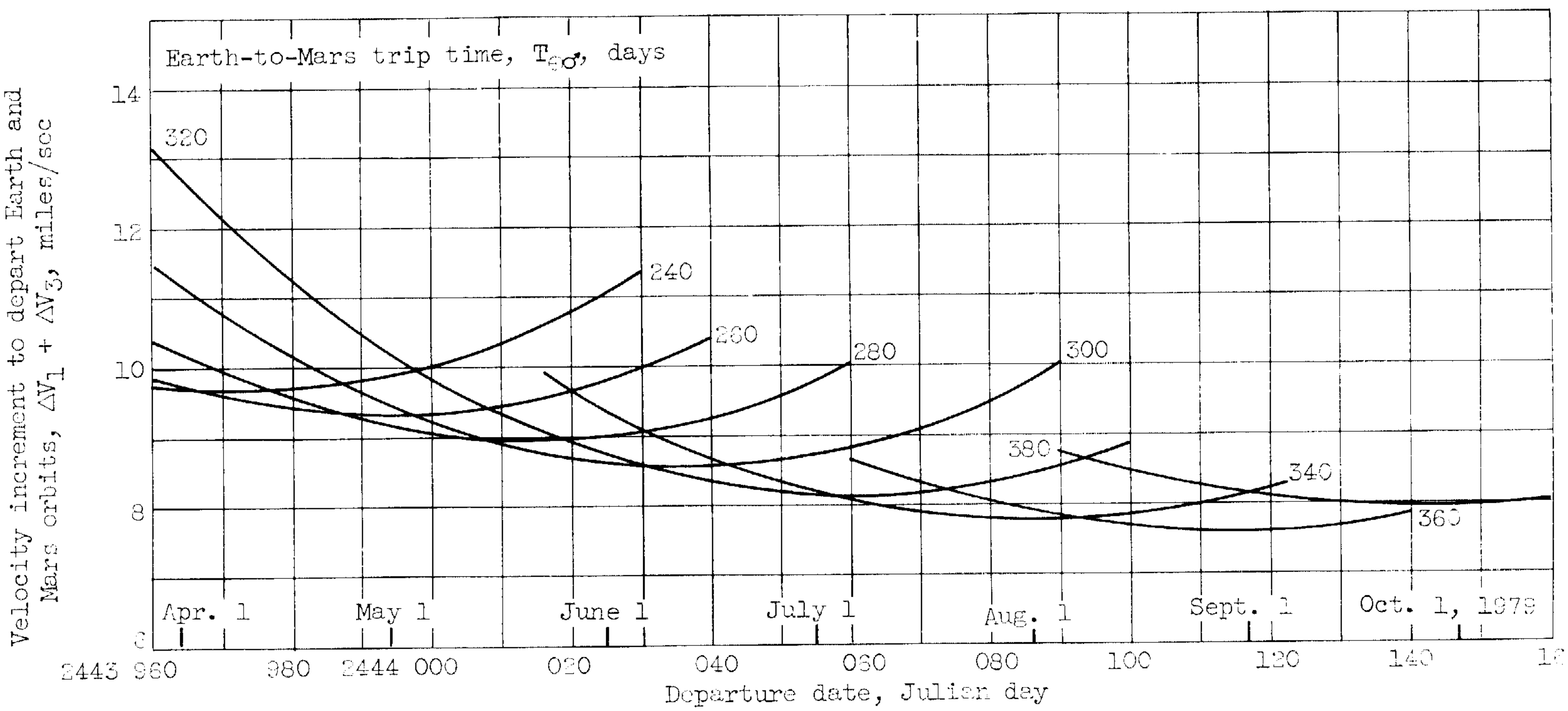
(b) Atmospheric braking at Earth.

Figure 25. - Continued. Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



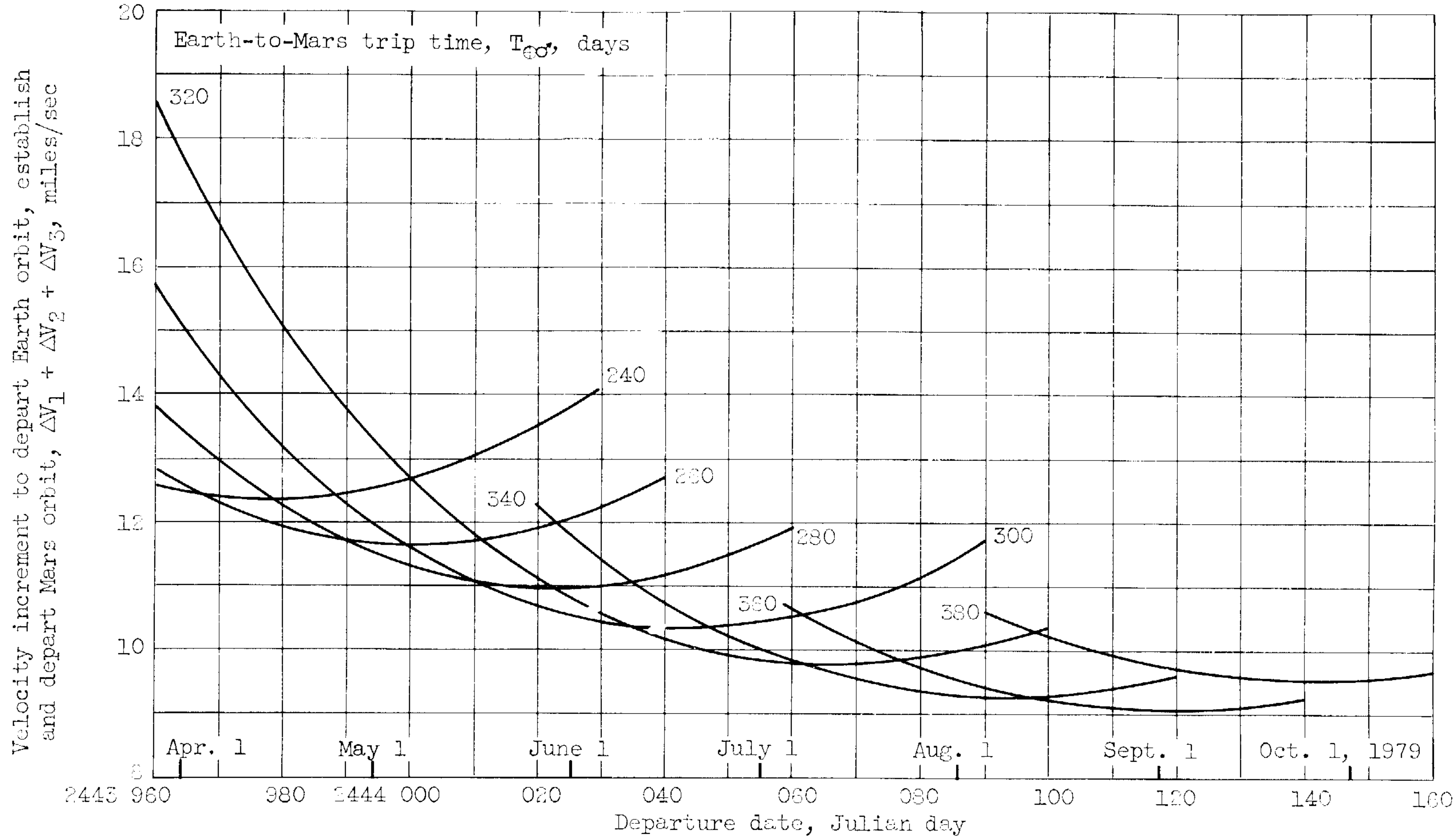
(c) All propulsive braking.

Figure 2?. - Concluded. Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



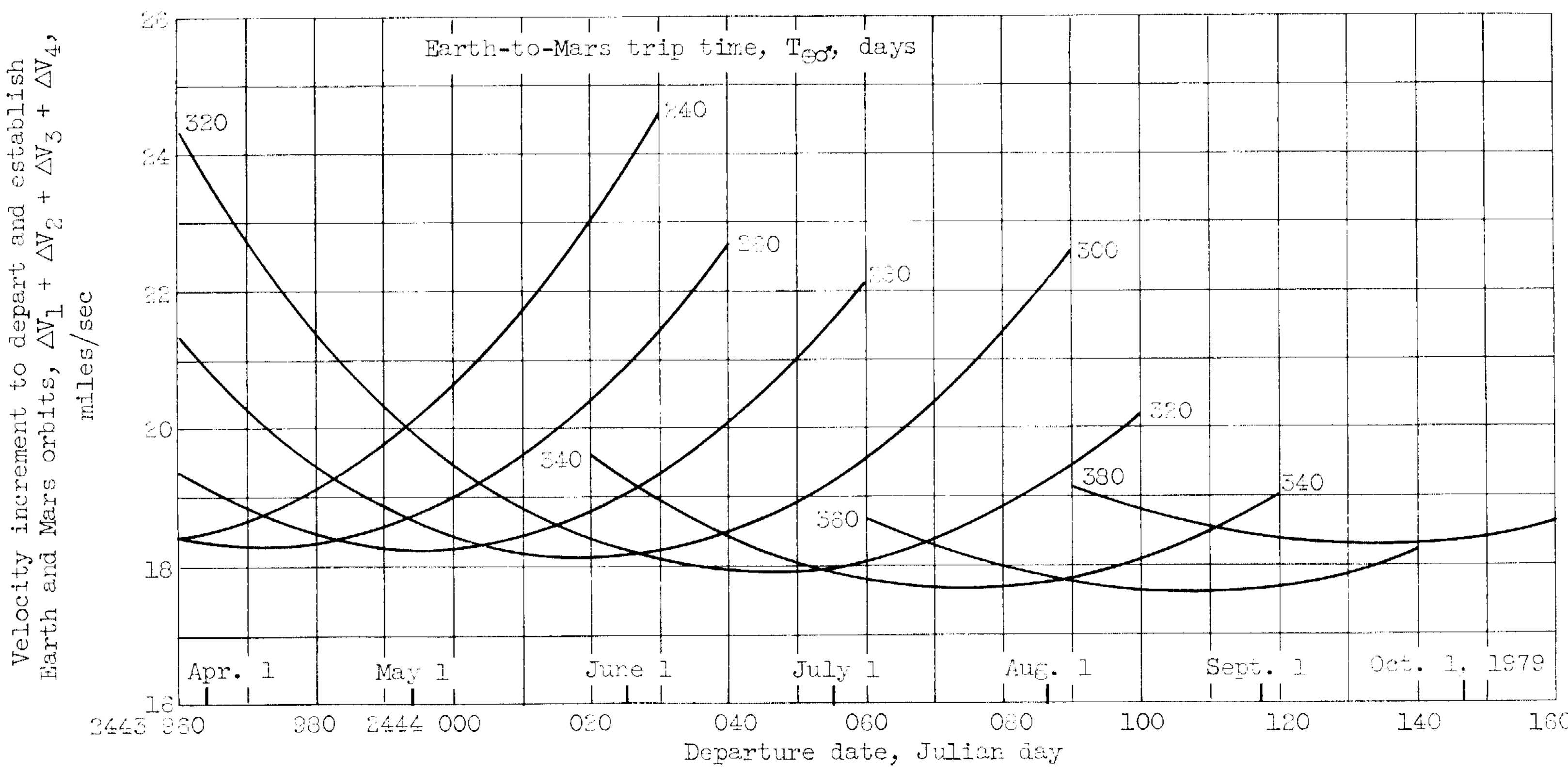
(a) Atmospheric braking at Mars and Earth.

Figure [illegible]. - Velocity increments for 300-day round trip to Mars. Wait time in Mars orbit, 40 days.



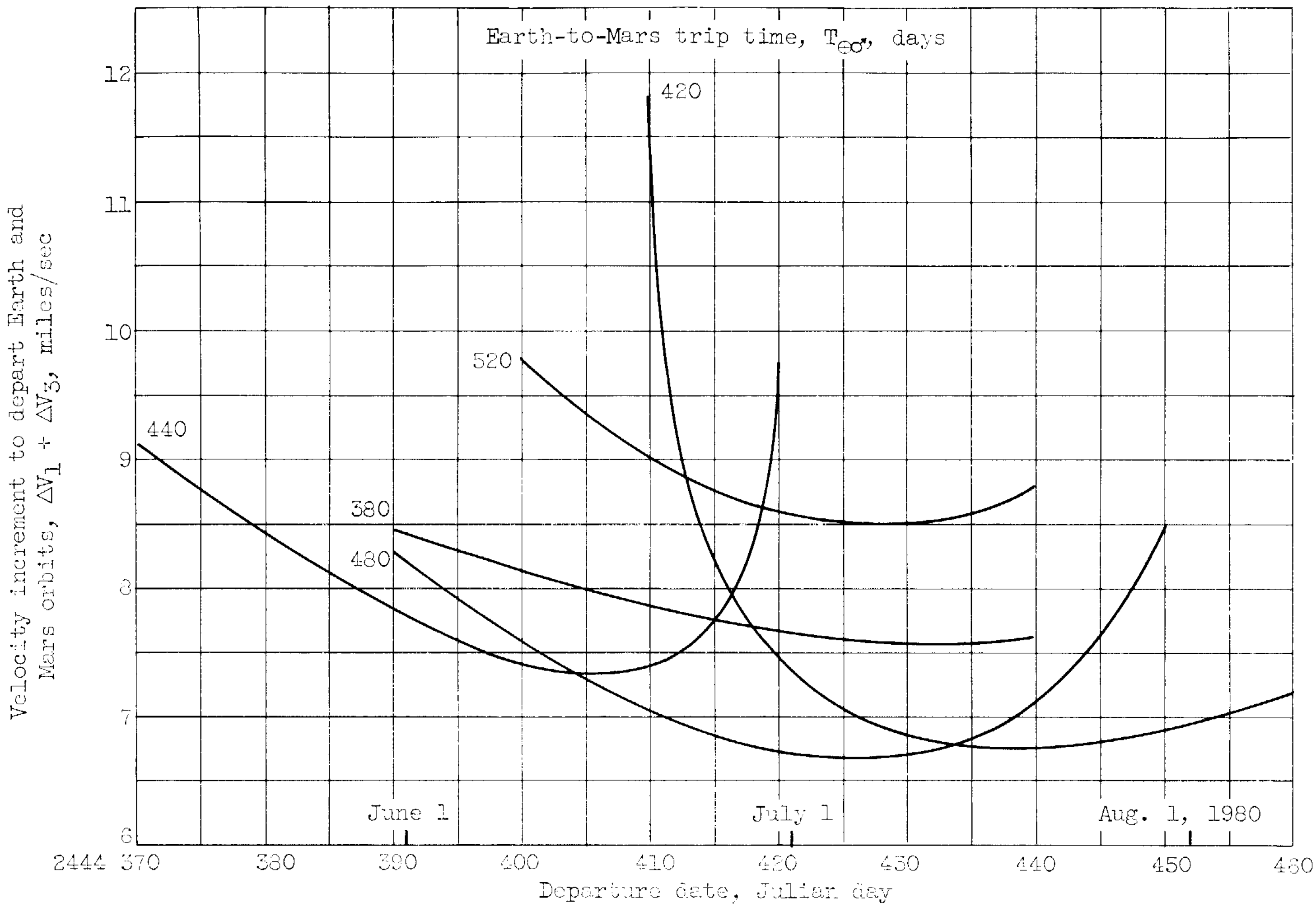
(b) Atmospheric braking at Earth.

Figure 26. - Continued. Velocity increments for 600-day round trip to Mars. Wait time in Mars orbit, 40 days.



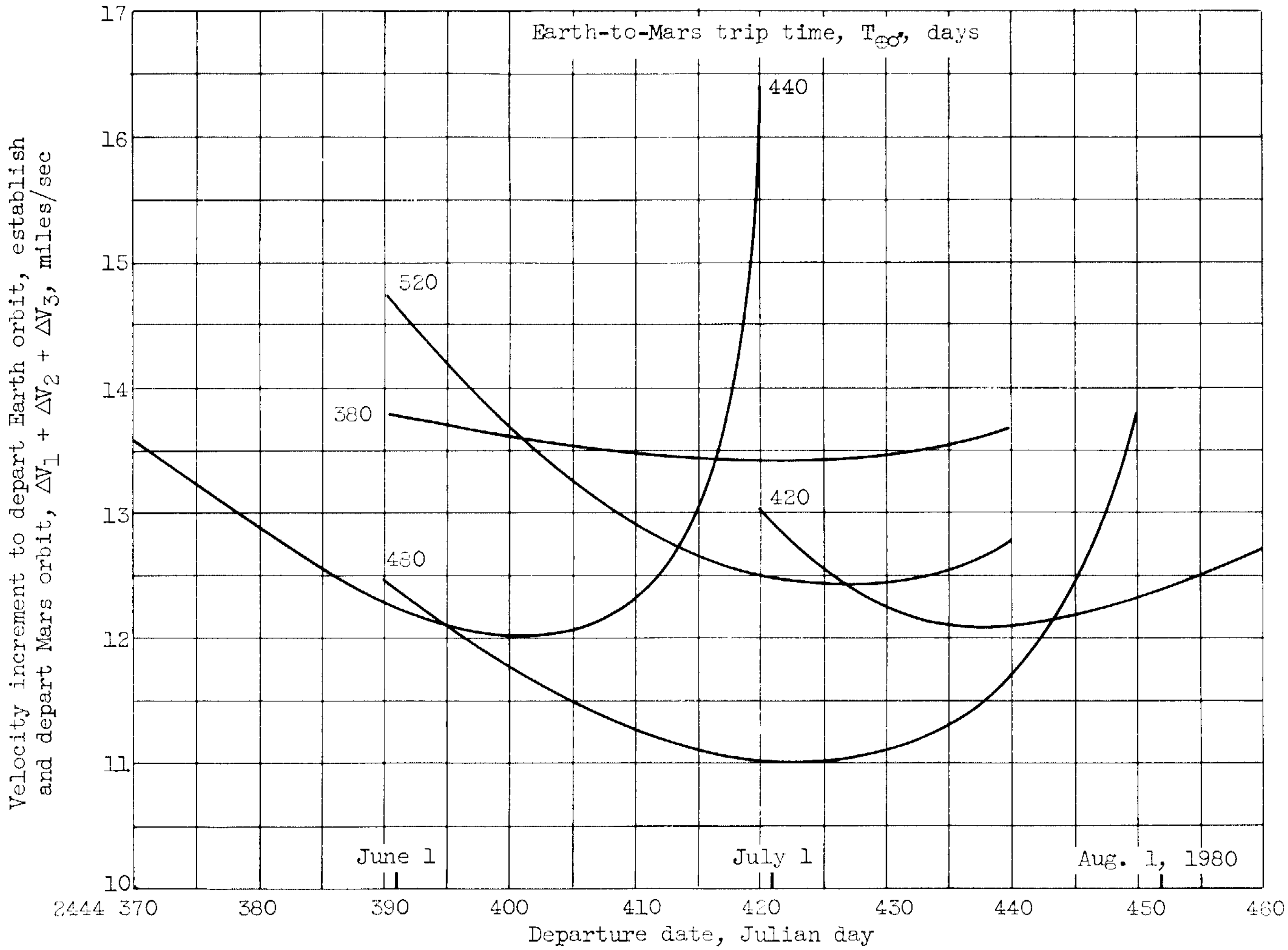
(c) All propulsive braking.

Figure 36. - Concluded. Velocity increments for 600-day round trip to Mars. Wait time in Mars orbit, 40 days.



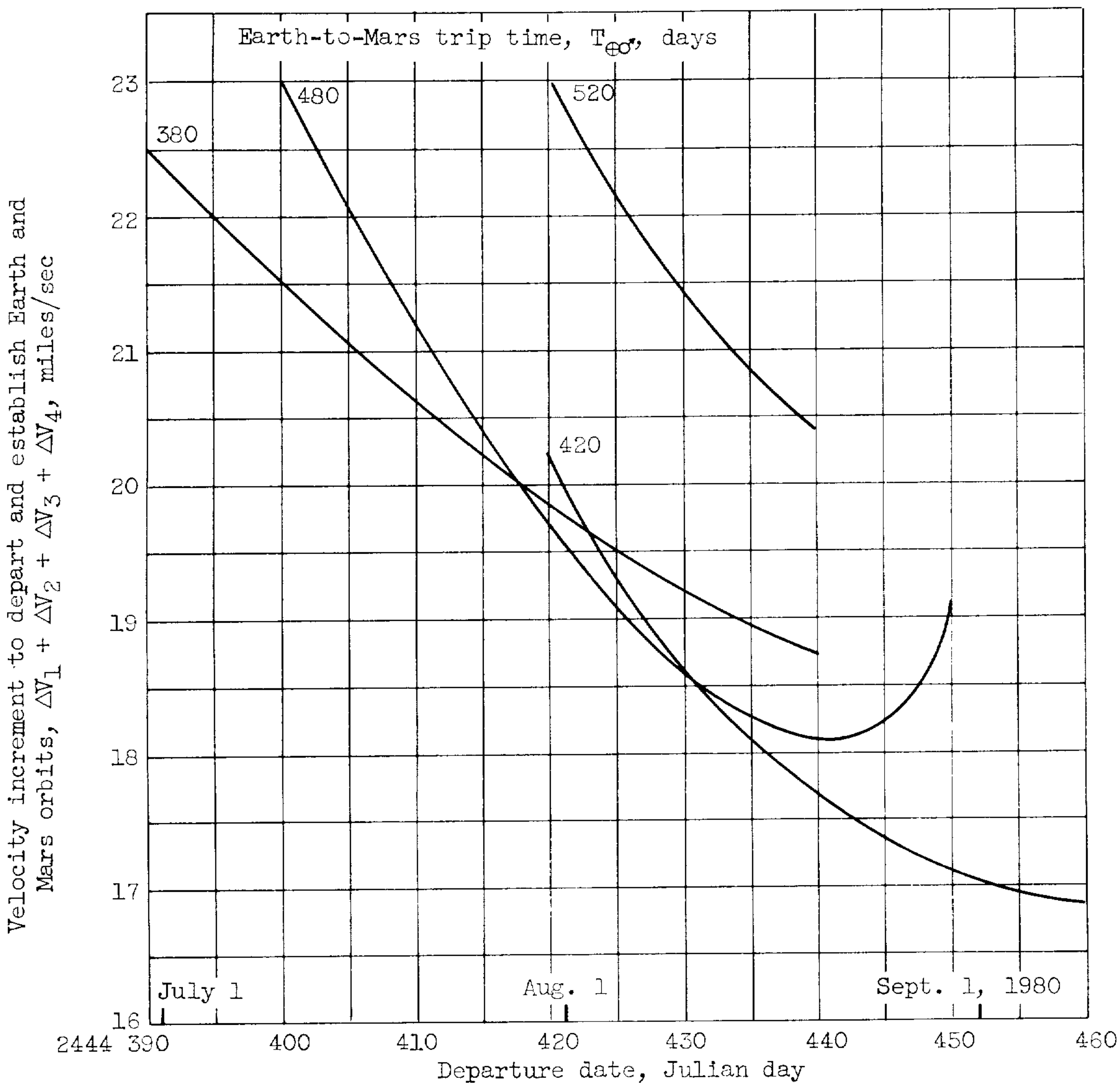
(a) Atmospheric braking at Mars and Earth.

Figure 27. - Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 40 days.



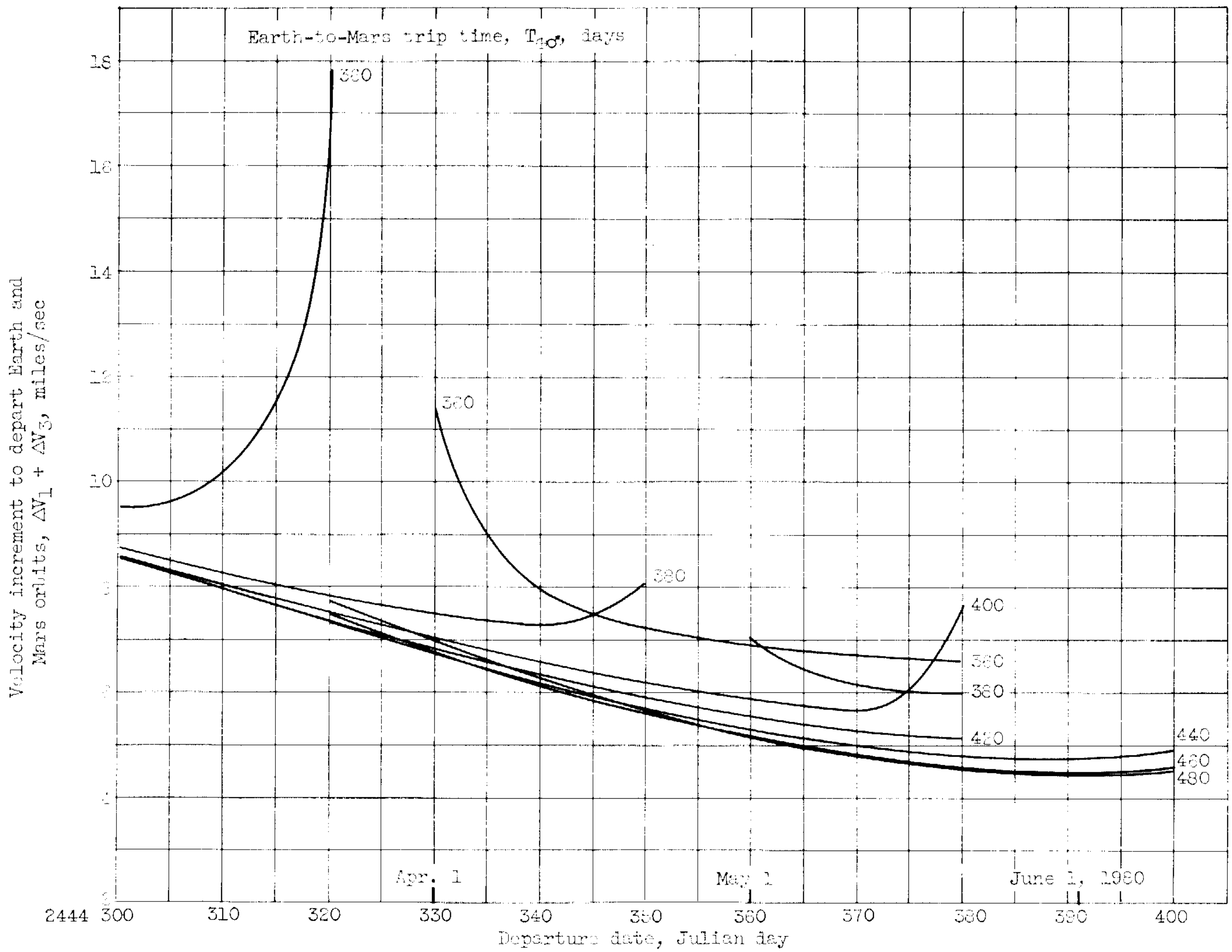
(b) Atmospheric braking at Earth.

Figure 27. - Continued. Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 40 days.



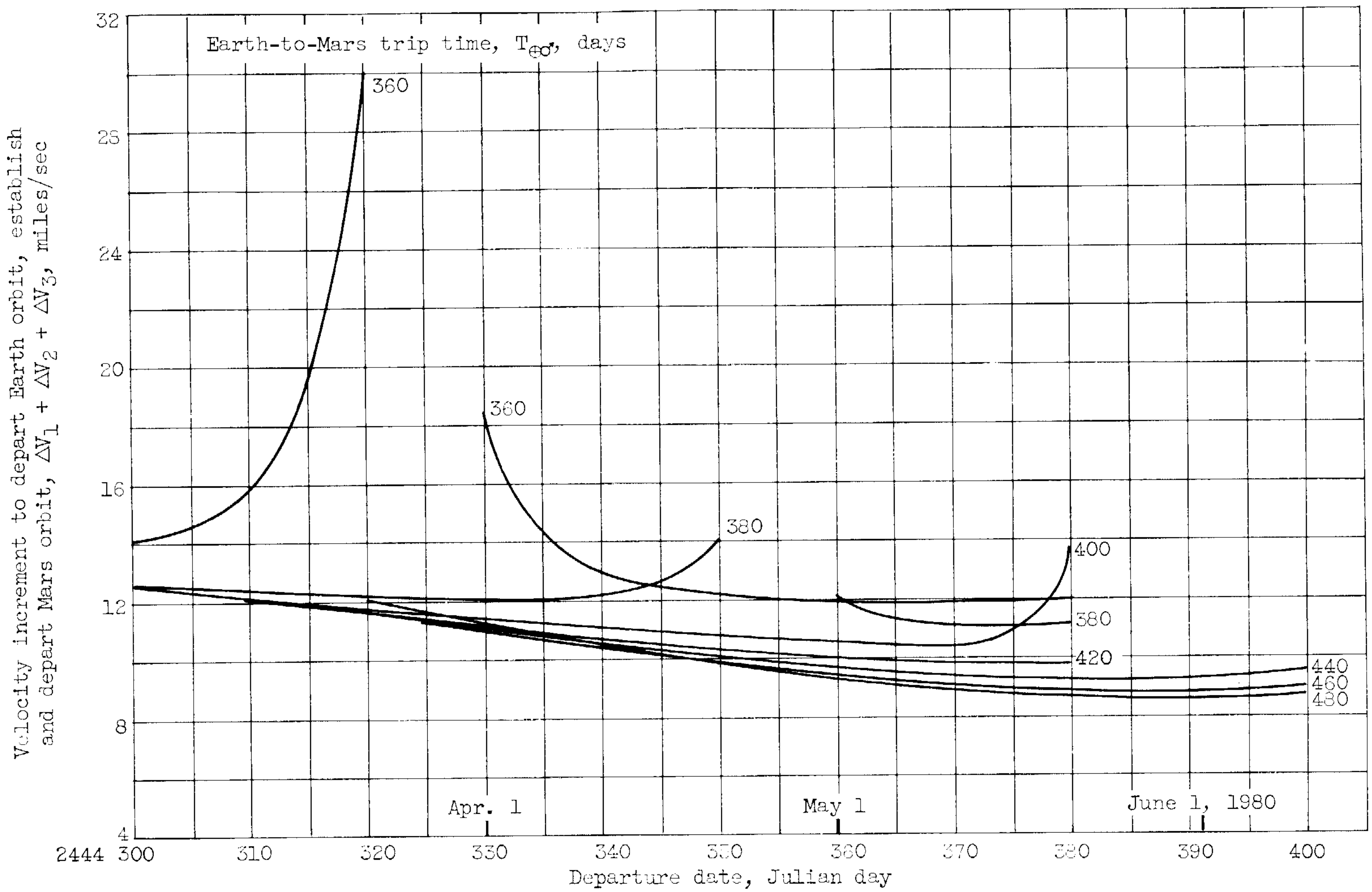
(c) All propulsive braking.

Figure 27. - Concluded. Velocity increments for 640-day round trip to Mars. Wait time in Mars orbit, 40 days.



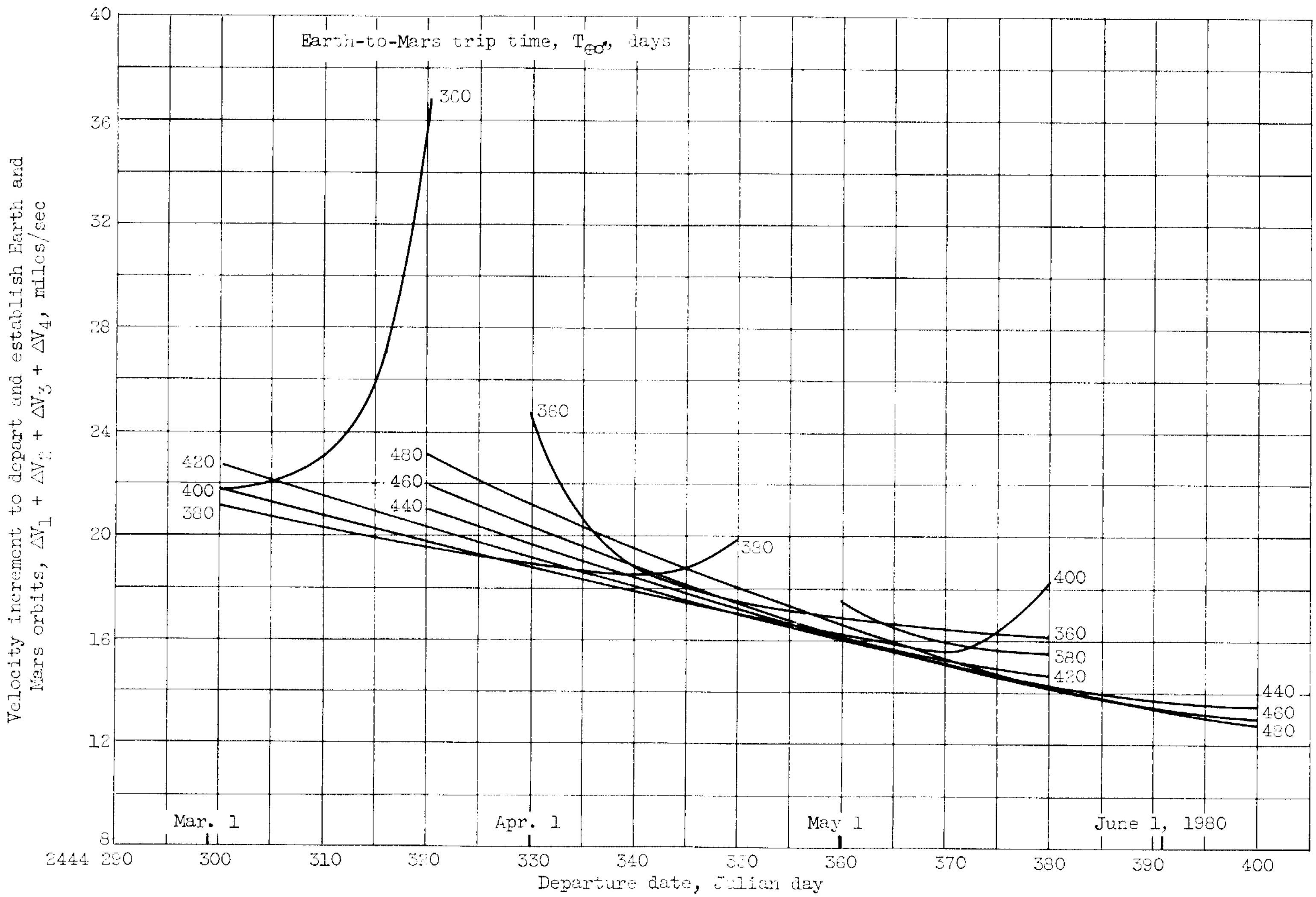
(a) Atmospheric braking at Mars and Earth.

Figure 28. - Velocity increments for 760-day round trip to Mars. Wait time in Mars orbit, 40 days.



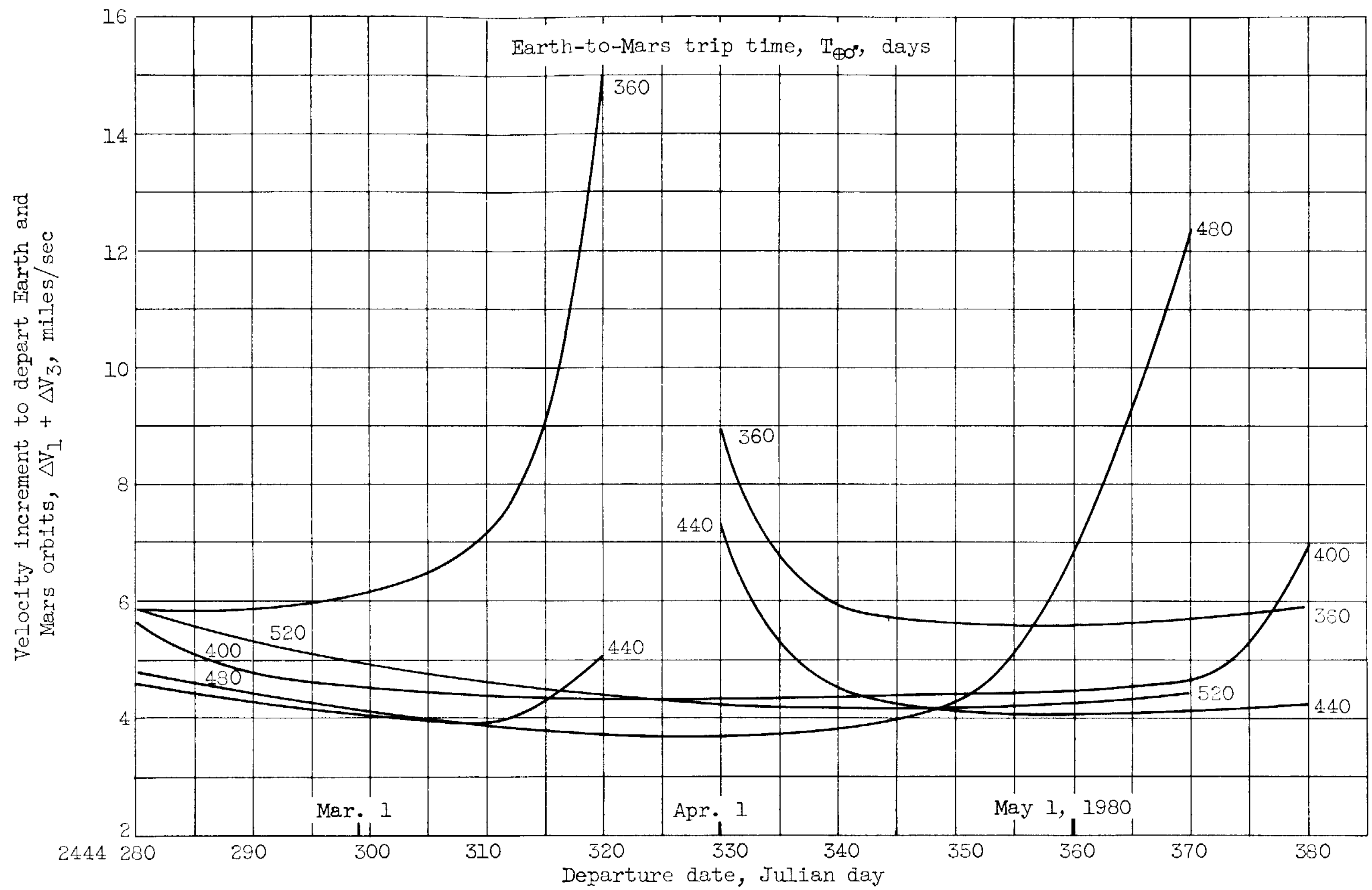
(b) Atmospheric braking at Earth.

Figure 28. - Continued. Velocity increments for 760-day round trip to Mars. Wait time in Mars orbit, 40 days.



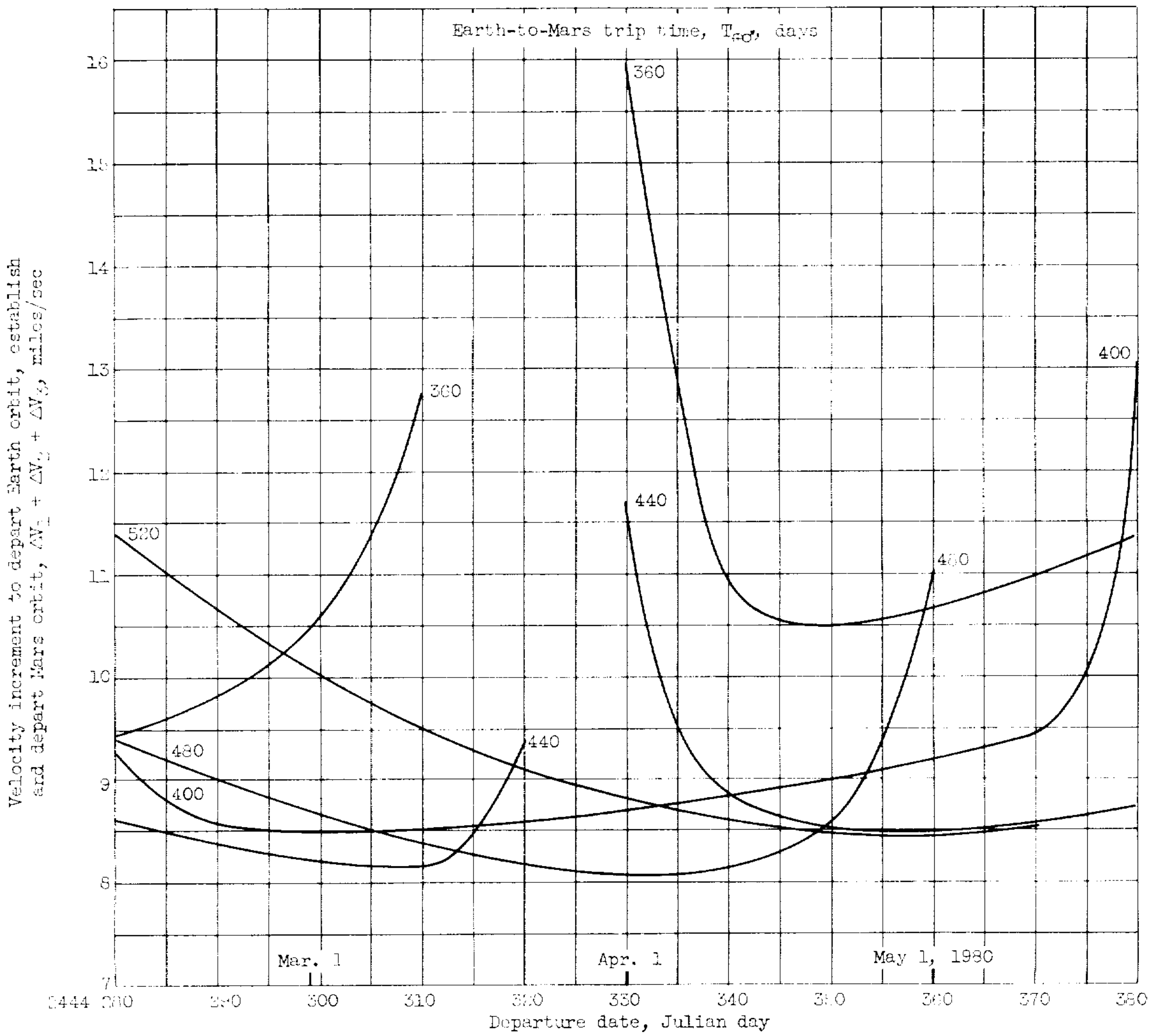
(c) All propulsive braking.

Figure 23. - Concluded. Velocity increments for 760-day round trip to Mars. Wait time in Mars orbit, 40 days.



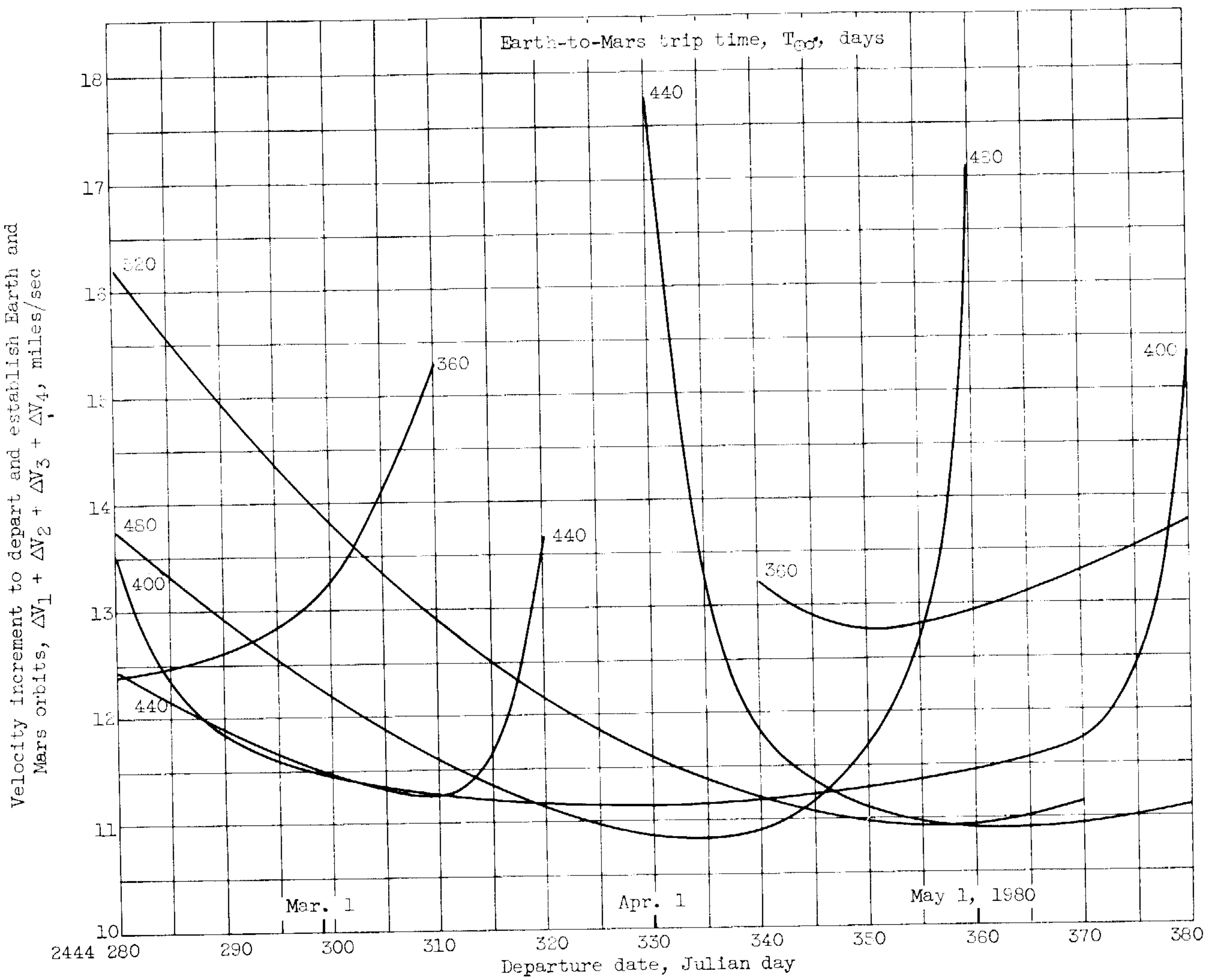
(a) Atmospheric braking at Mars and Earth.

Figure 29. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.



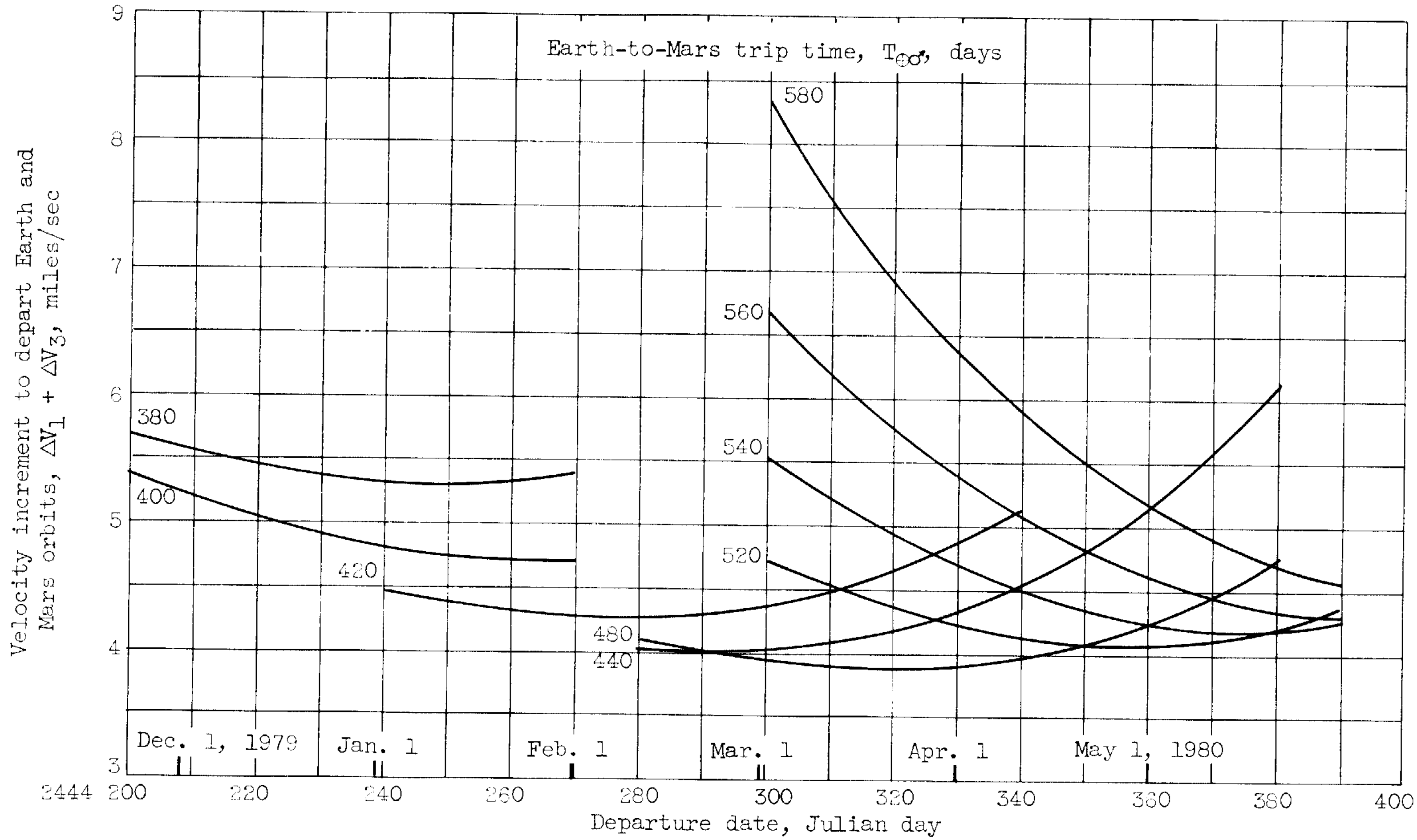
(b) Atmospheric braking at Earth.

Figure 29. - Continued. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.



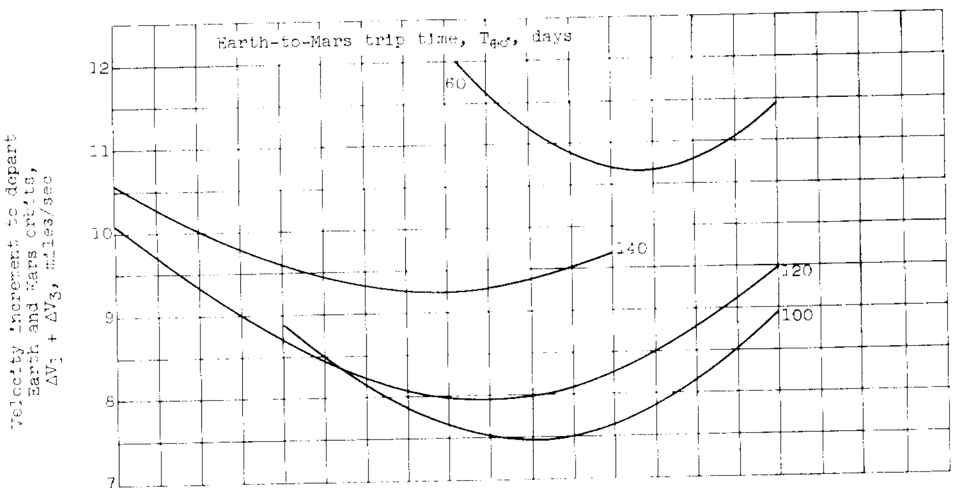
(c) All propulsive braking.

Figure 29. - Concluded. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 40 days.

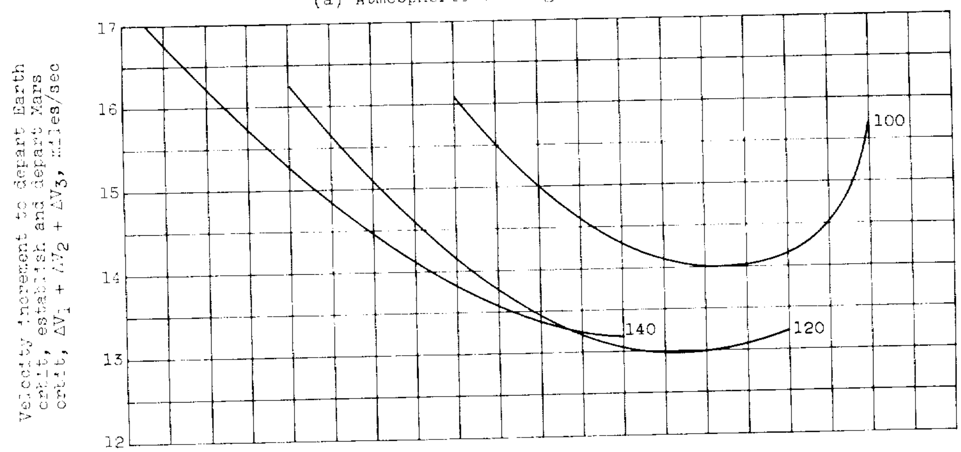


(a) Atmospheric braking at Mars and Earth.

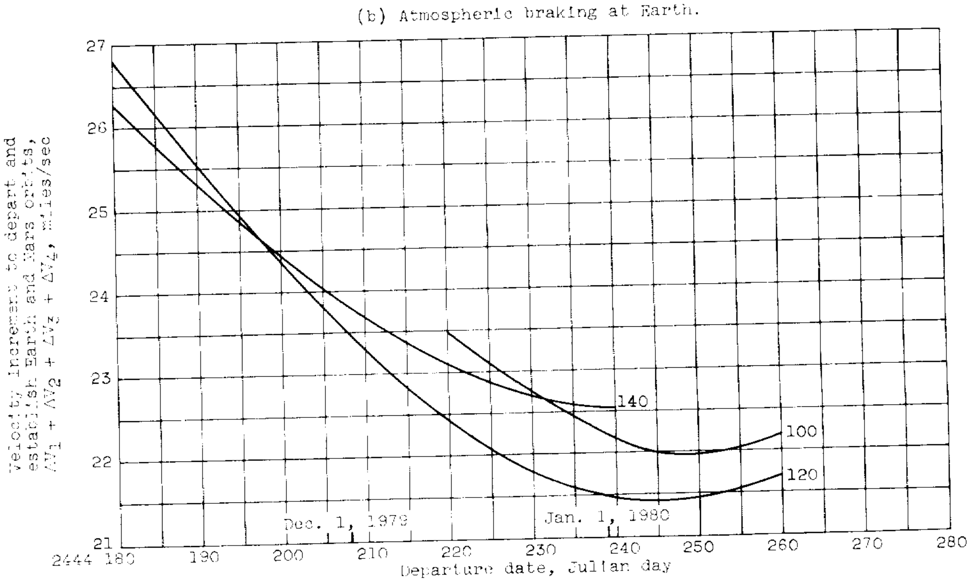
Figure 30. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 40 days.



(a) Atmospheric braking at Mars and Earth.



(b) Atmospheric braking at Earth.



(c) All propulsive braking.

Figure 31. - Velocity increments for 400-day round trip to Mars. Wait time in Mars orbit, 100 days.

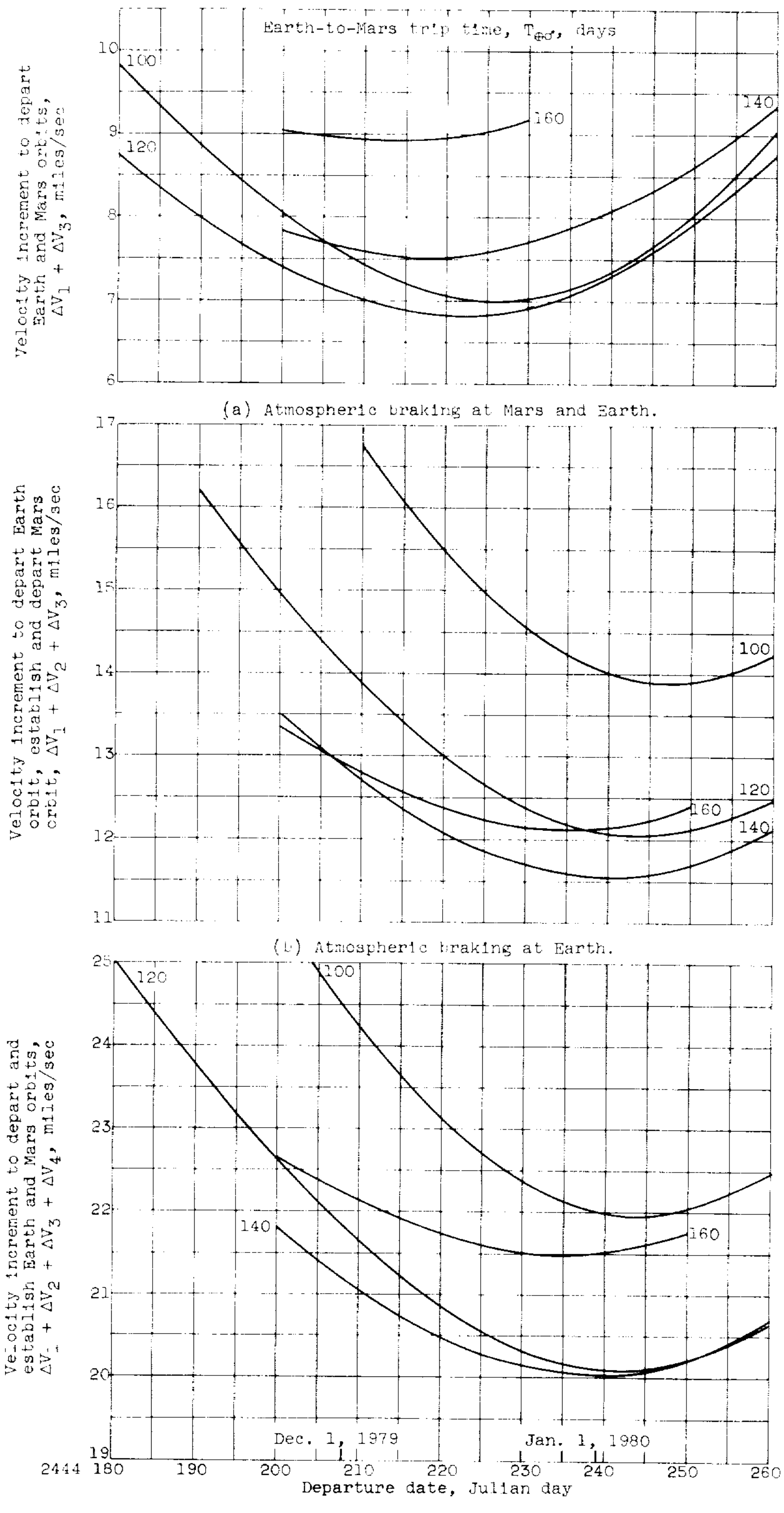
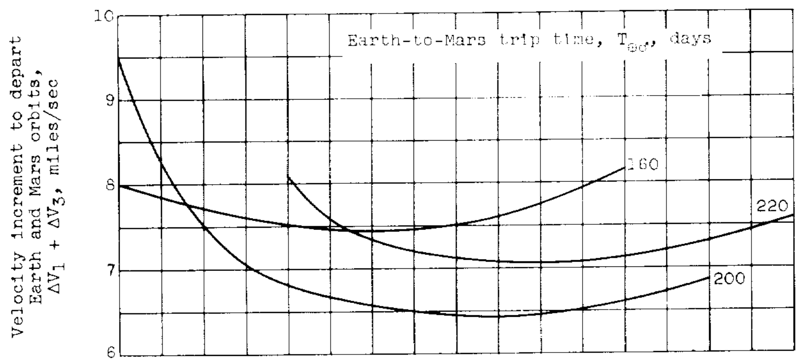
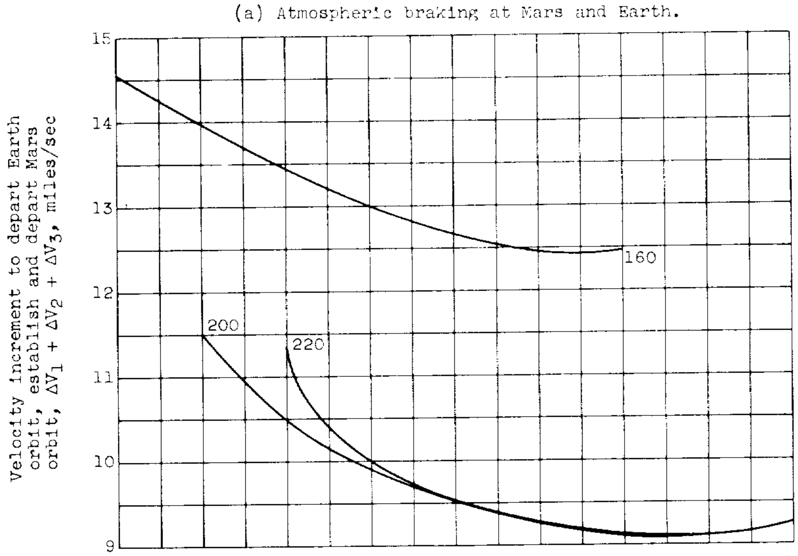


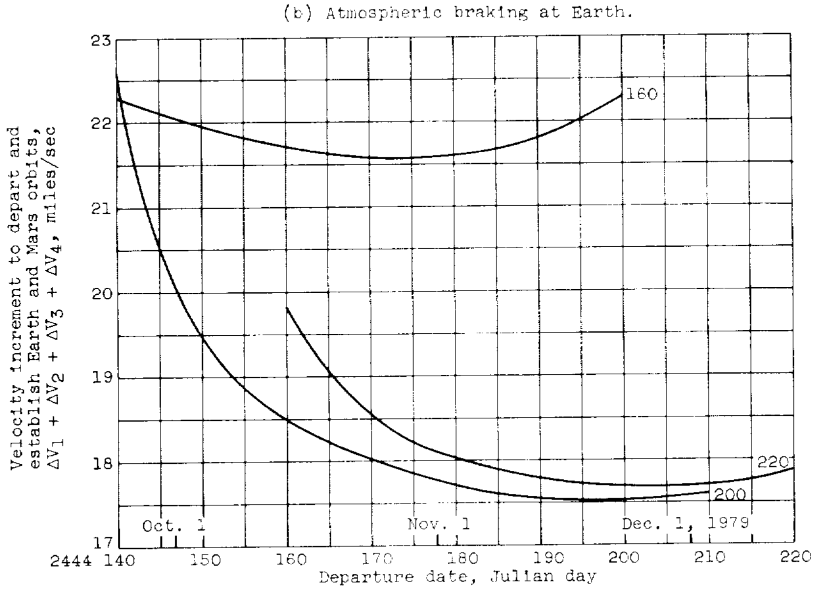
Figure 32. - Velocity increments for 420-day round trip to Mars. Wait time in Mars orbit, 100 days.



(a) Atmospheric braking at Mars and Earth.

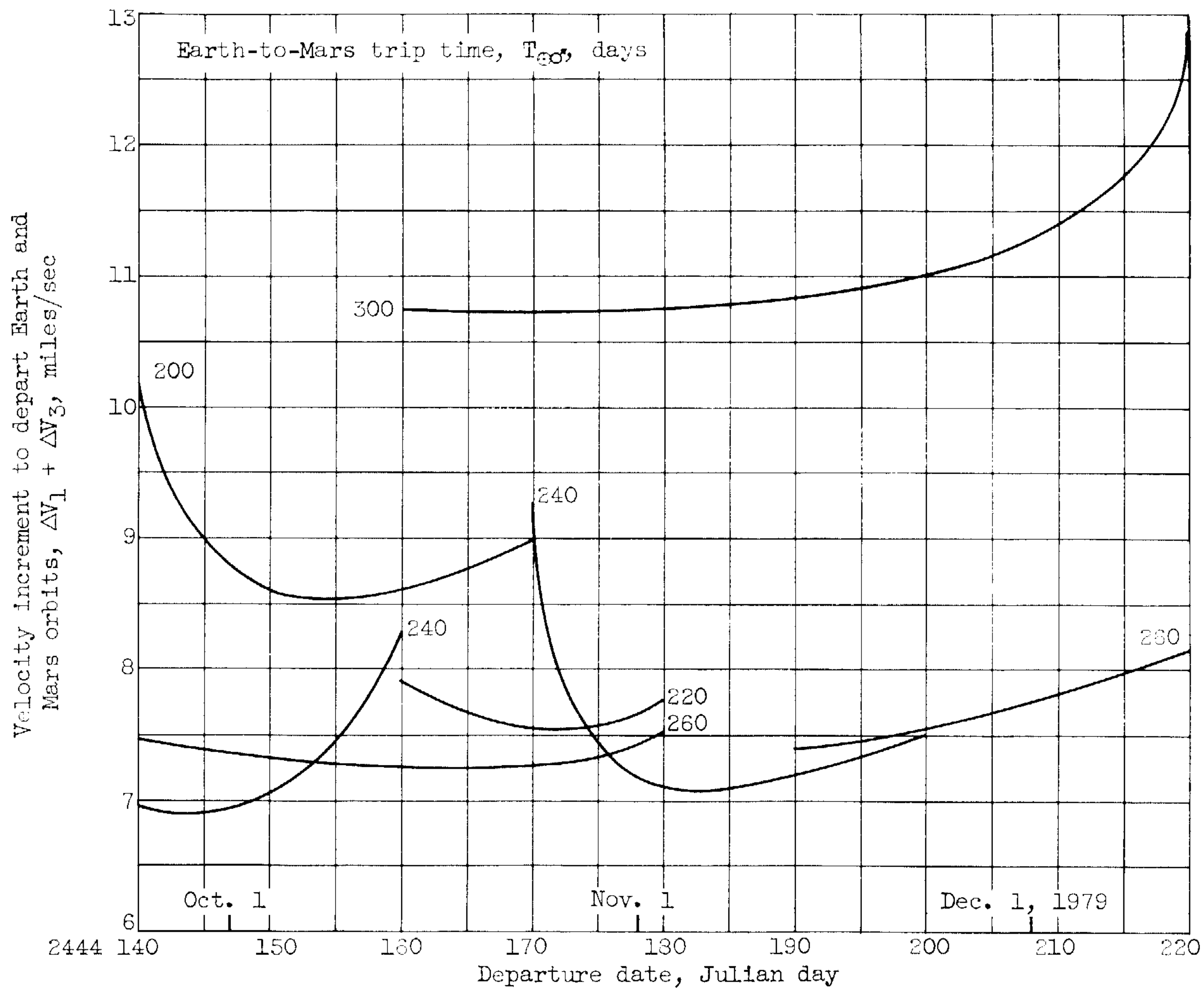


(b) Atmospheric braking at Earth.



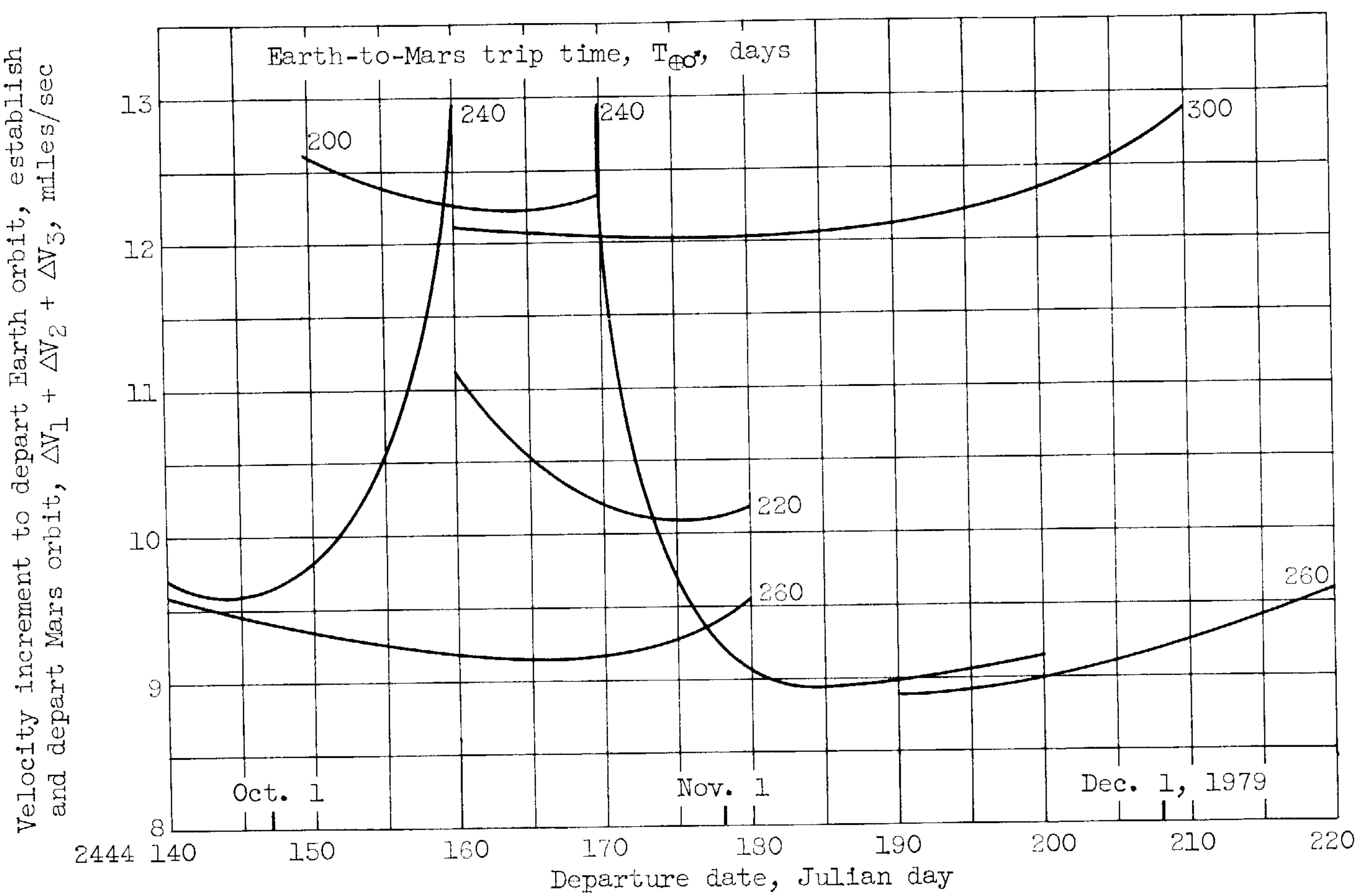
(c) All propulsive braking.

Figure 33. - Velocity increments for 500-day round trip to Mars. Wait time in Mars orbit, 100 days.



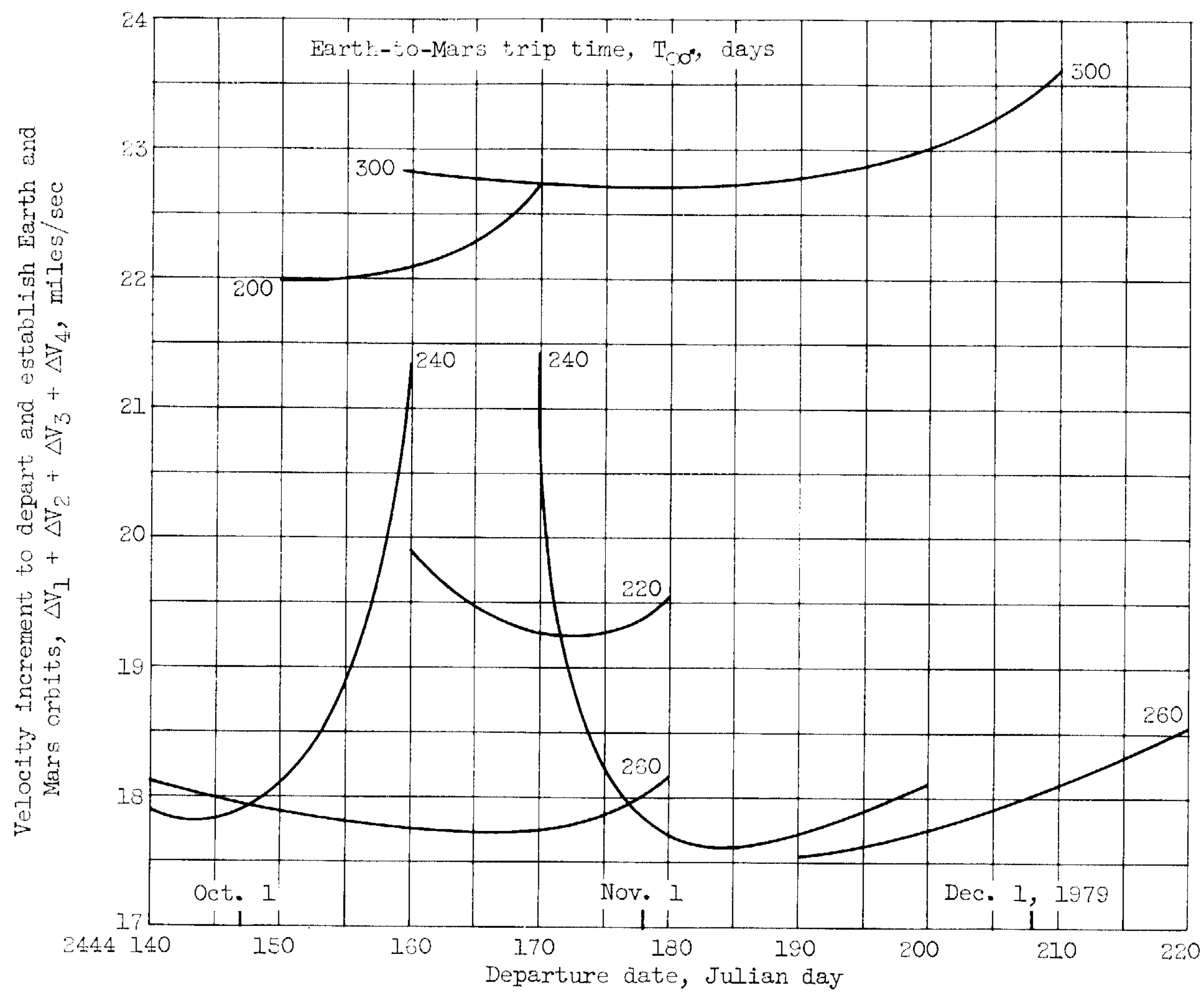
(a) Atmospheric braking at Mars and Earth.

Figure 34. - Velocity increments for 540-day round trip to Mars. Wait time in Mars orbit, 100 days.



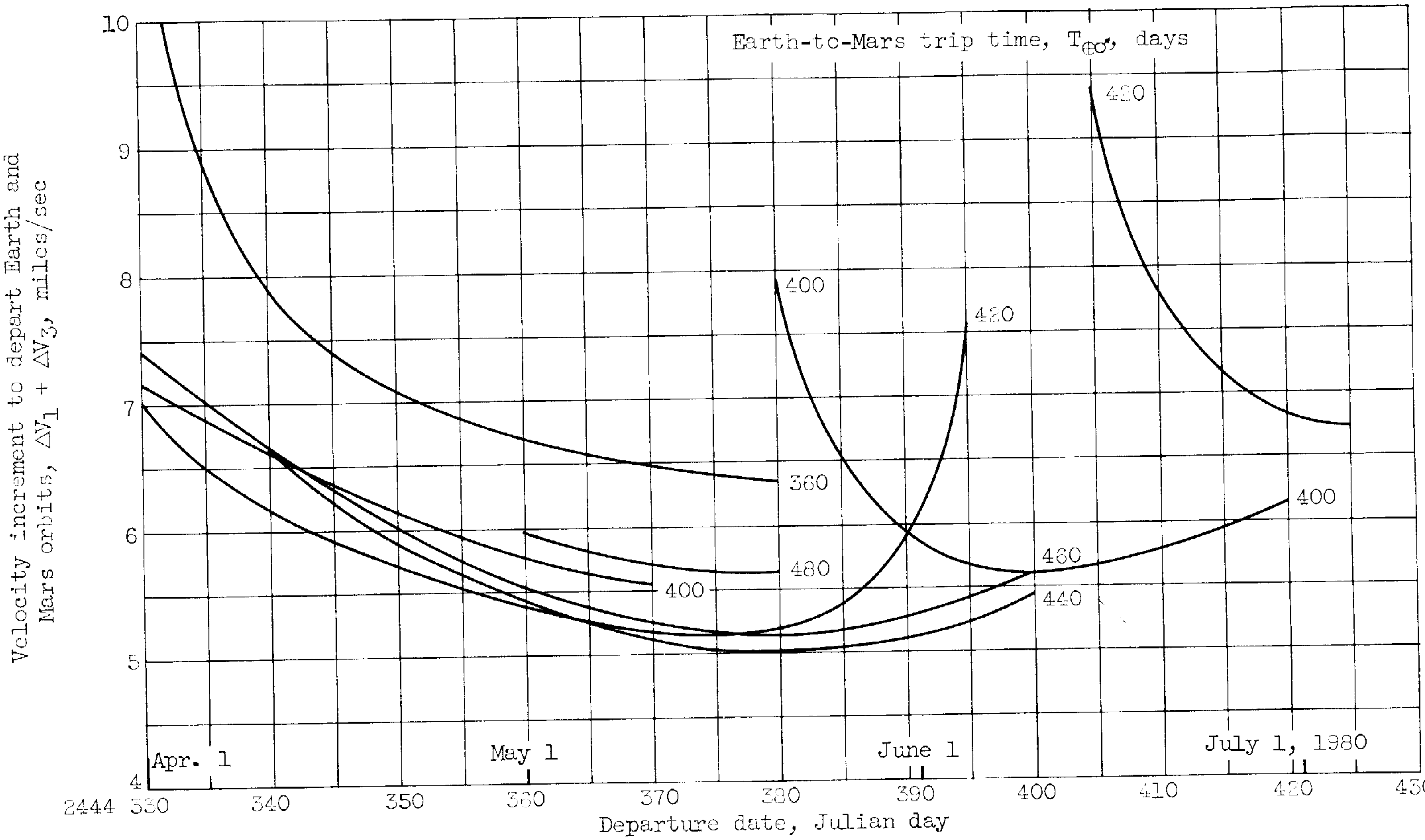
(b) Atmospheric braking at Earth.

Figure 34. - Continued. Velocity increments for 540-day round trip to Mars. Wait time in Mars orbit, 100 days.



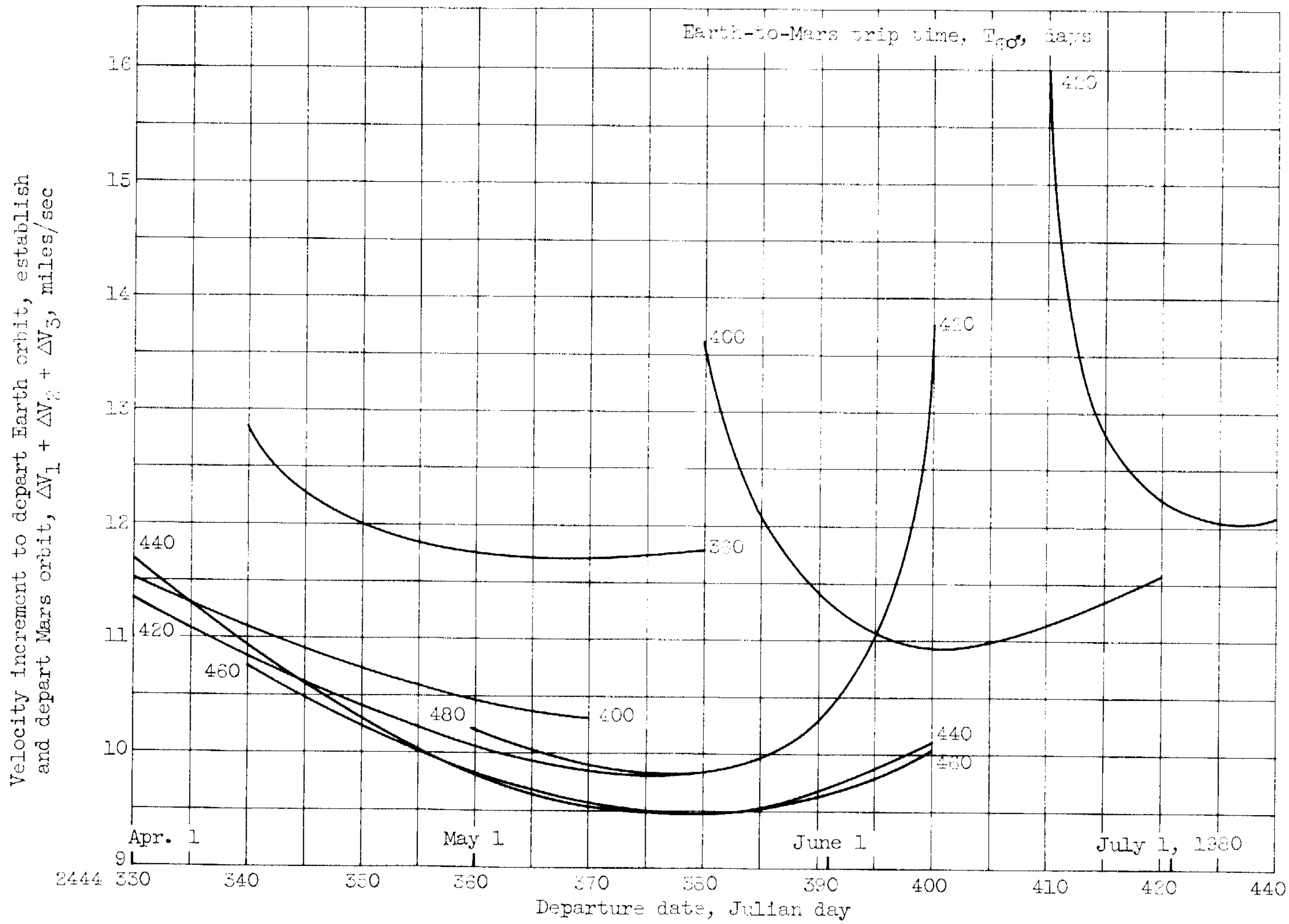
(c) All propulsive braking.

Figure 34. - Concluded. Velocity increments for 540-day round trip to Mars. Wait time in Mars orbit, 100 days.



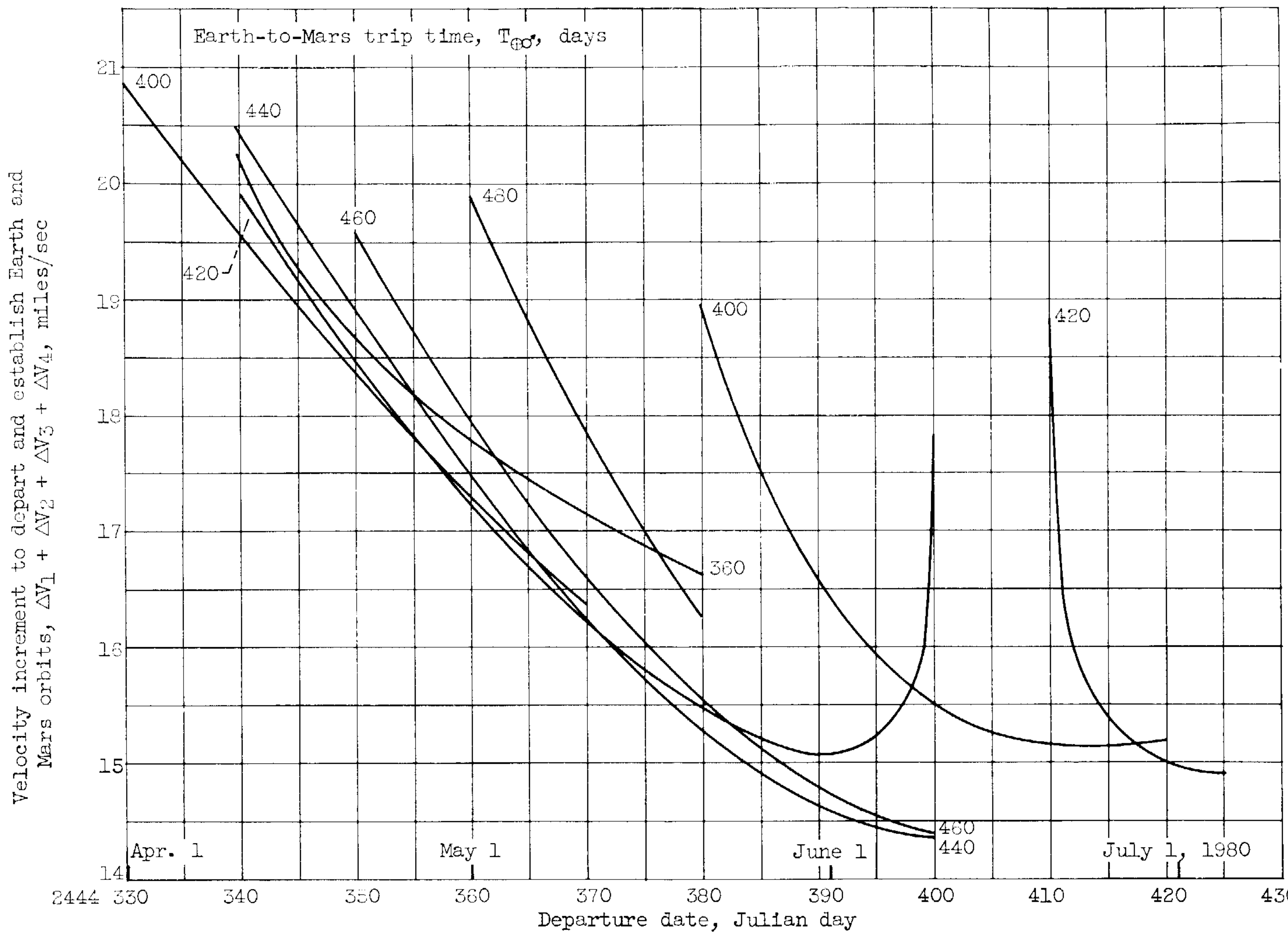
(a) Atmospheric braking at Mars and Earth.

Figure 35. - Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 100 days.



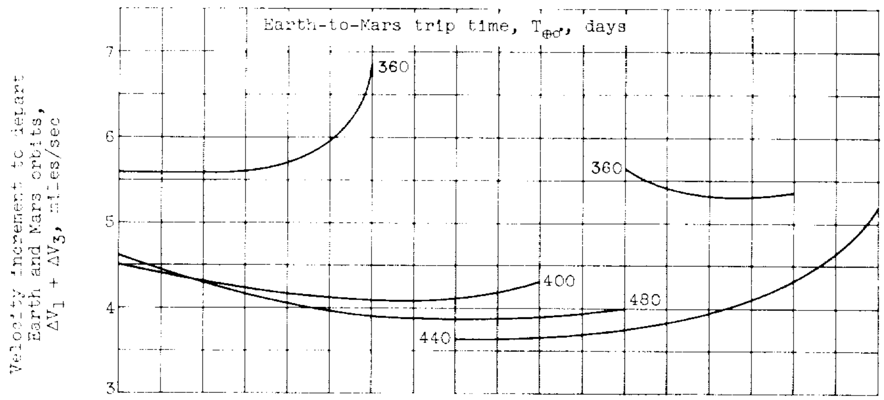
(b) Atmospheric braking at Earth.

Figure 35. - Continued. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 100 days.

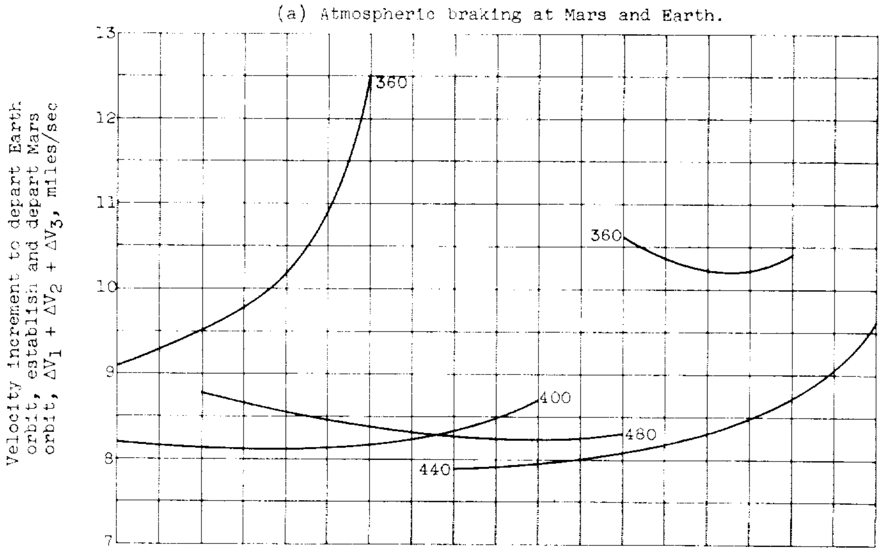


(c) All propulsive braking.

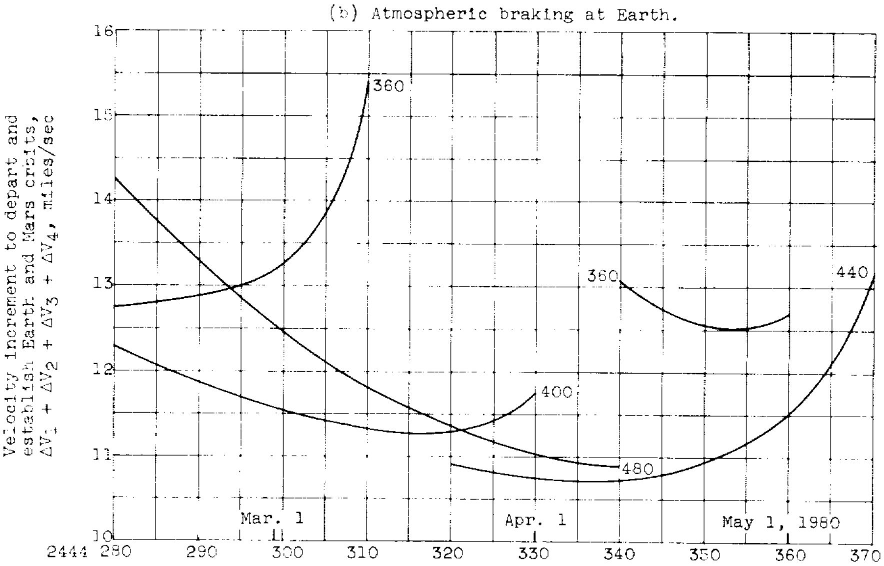
Figure 35. - Concluded. Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 100 days.



(a) Atmospheric braking at Mars and Earth.

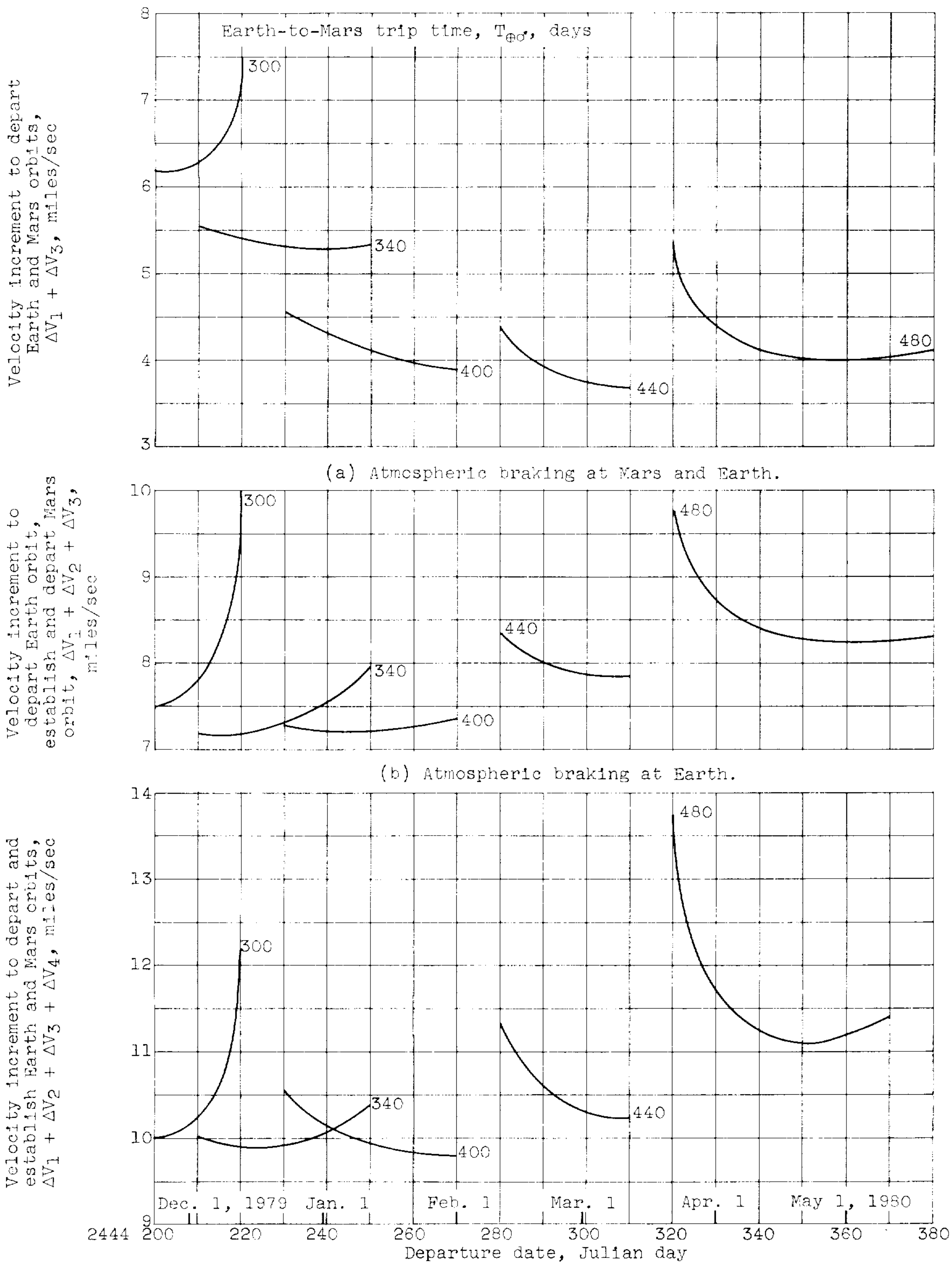


(b) Atmospheric braking at Earth.



(c) All propulsive braking.

Figure 36. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 100 days.

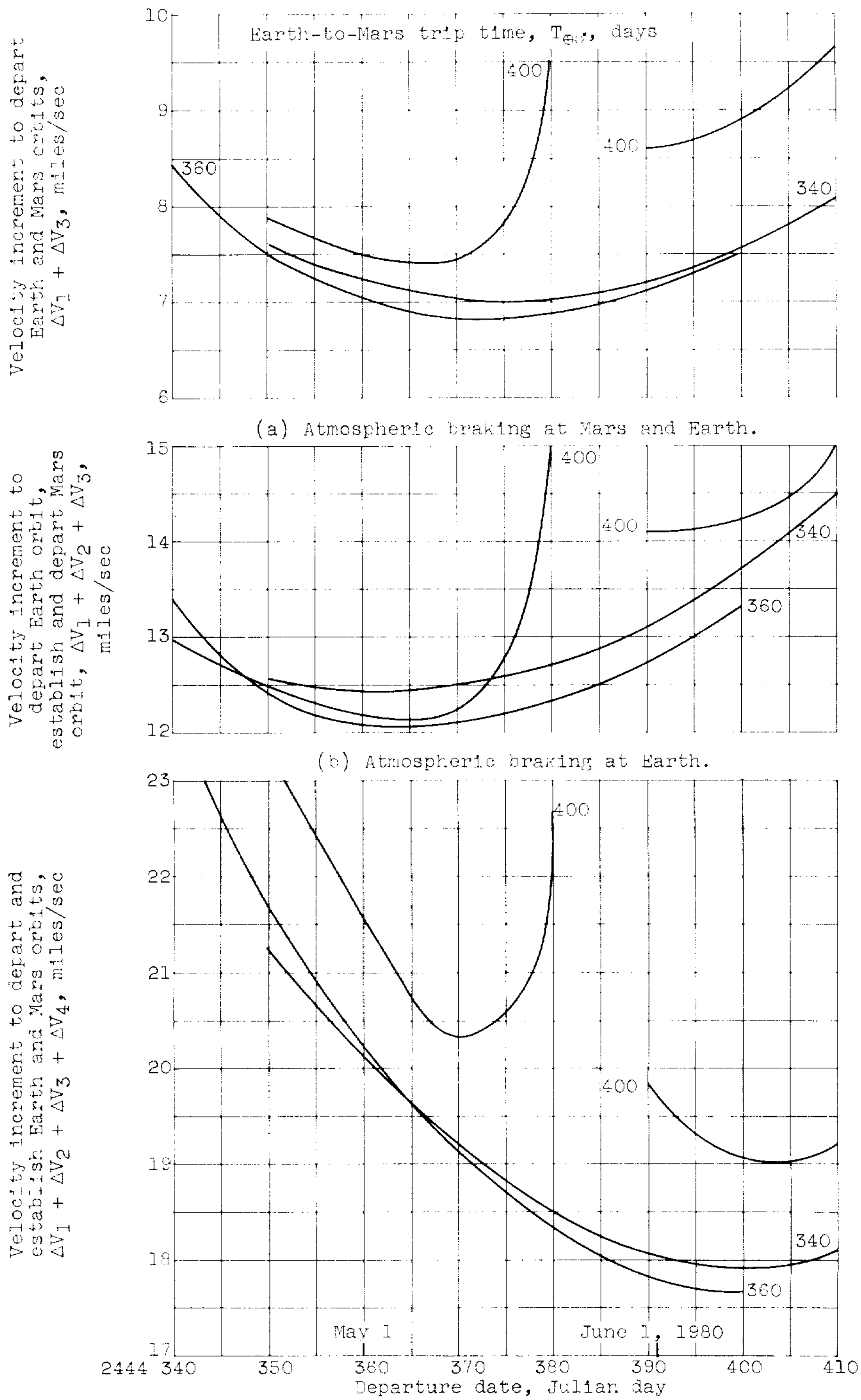


(a) Atmospheric braking at Mars and Earth.

(b) Atmospheric braking at Earth.

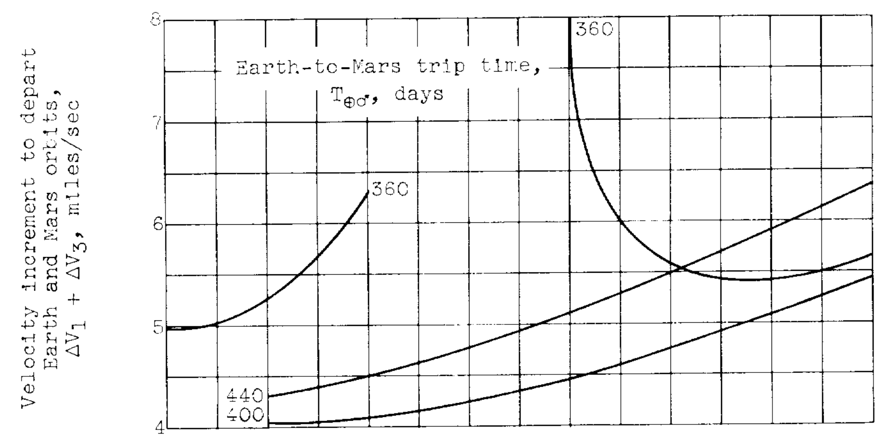
(c) All propulsive braking.

Figure 37. - Velocity increments for 860-day round trip to Mars. Wait time in Mars orbit, 100 days.

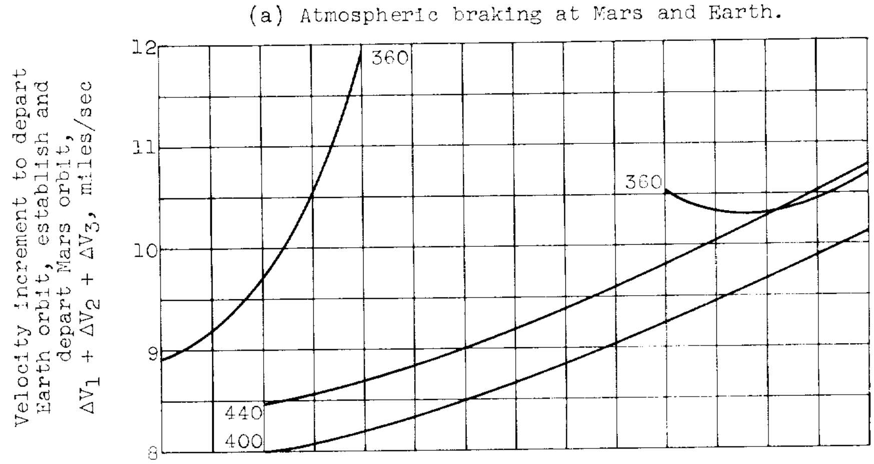


(c) All propulsive braking.

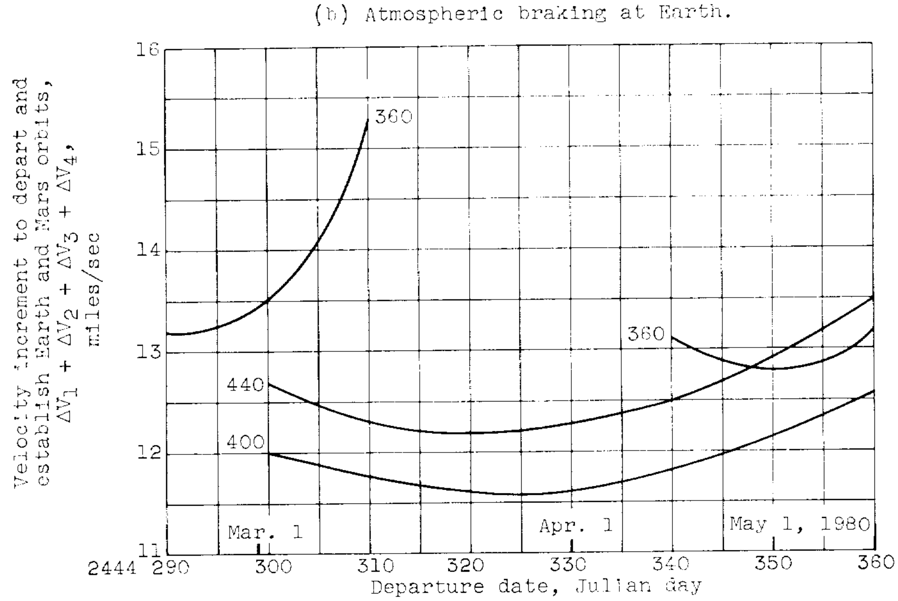
Figure 38. - Velocity increments for 700-day round trip to Mars. Wait time in Mars orbit, 200 days.



(a) Atmospheric braking at Mars and Earth.

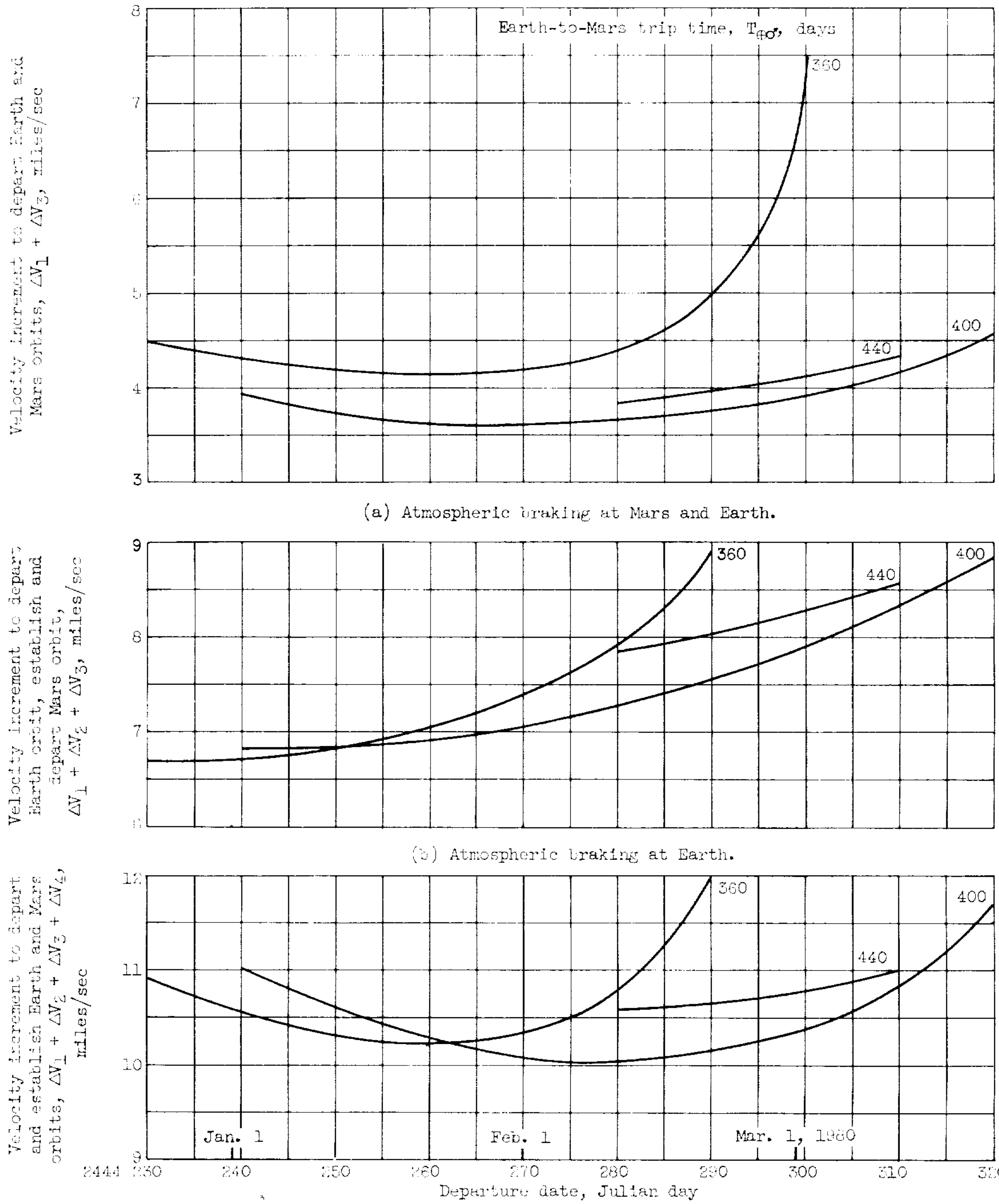


(b) Atmospheric braking at Earth.



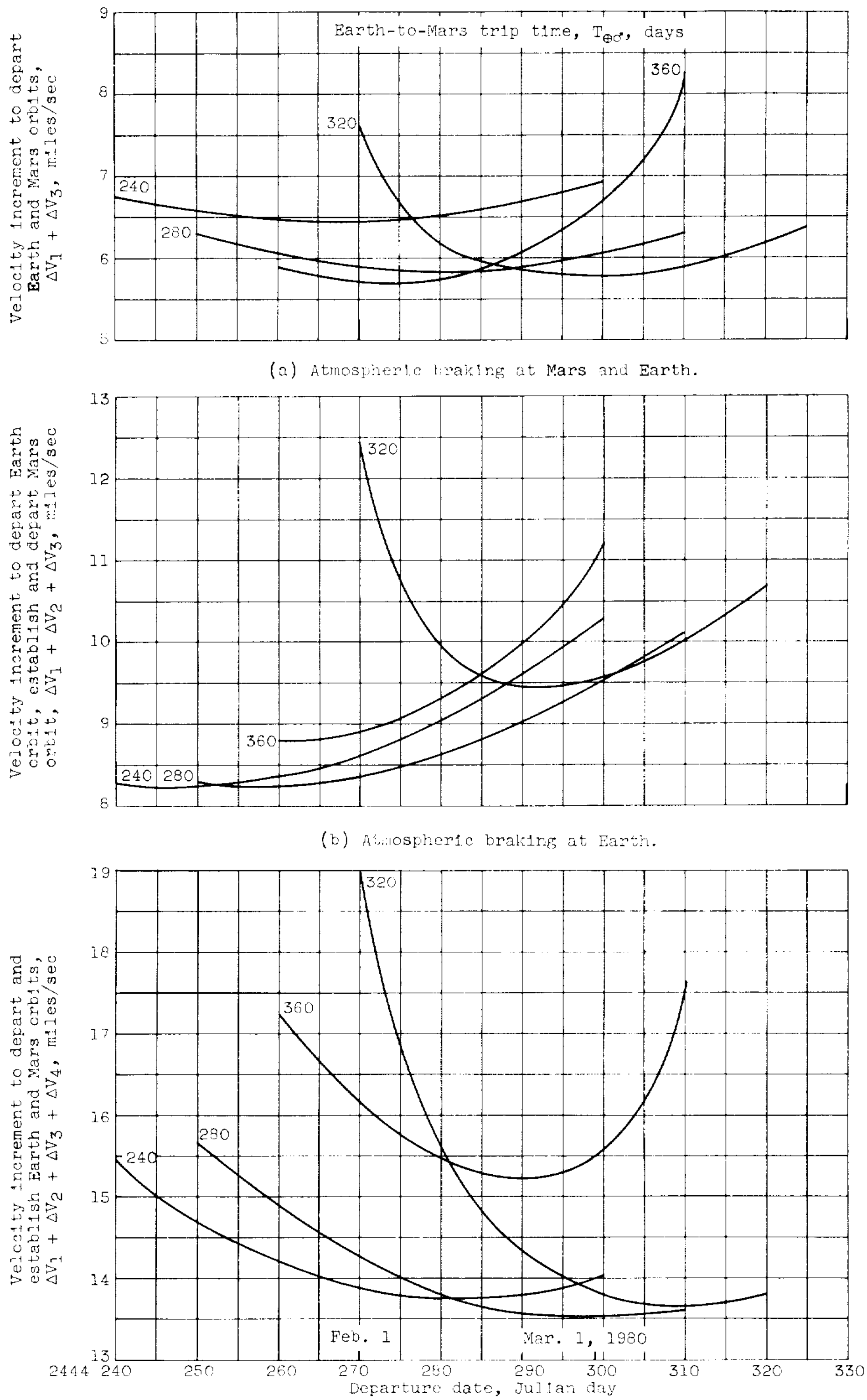
(c) All propulsive braking.

Figure 39. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 200 days.



(c) All propulsive braking.

Figure 40. - Velocity increments for 850-day round trip to Mars. Wait time in Mars orbit, 200 days.



(c) All propulsive braking.

Figure 41. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 310 days.

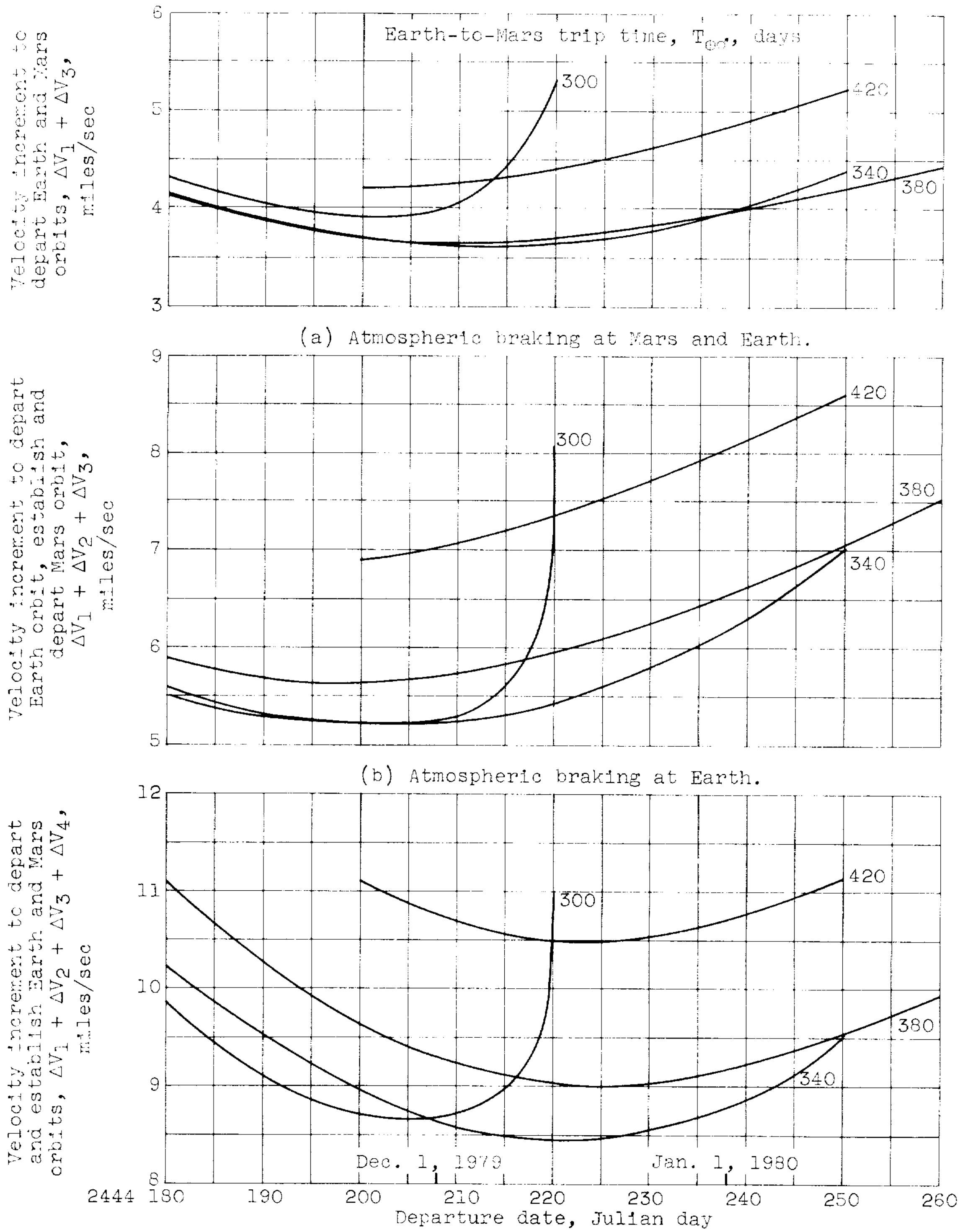
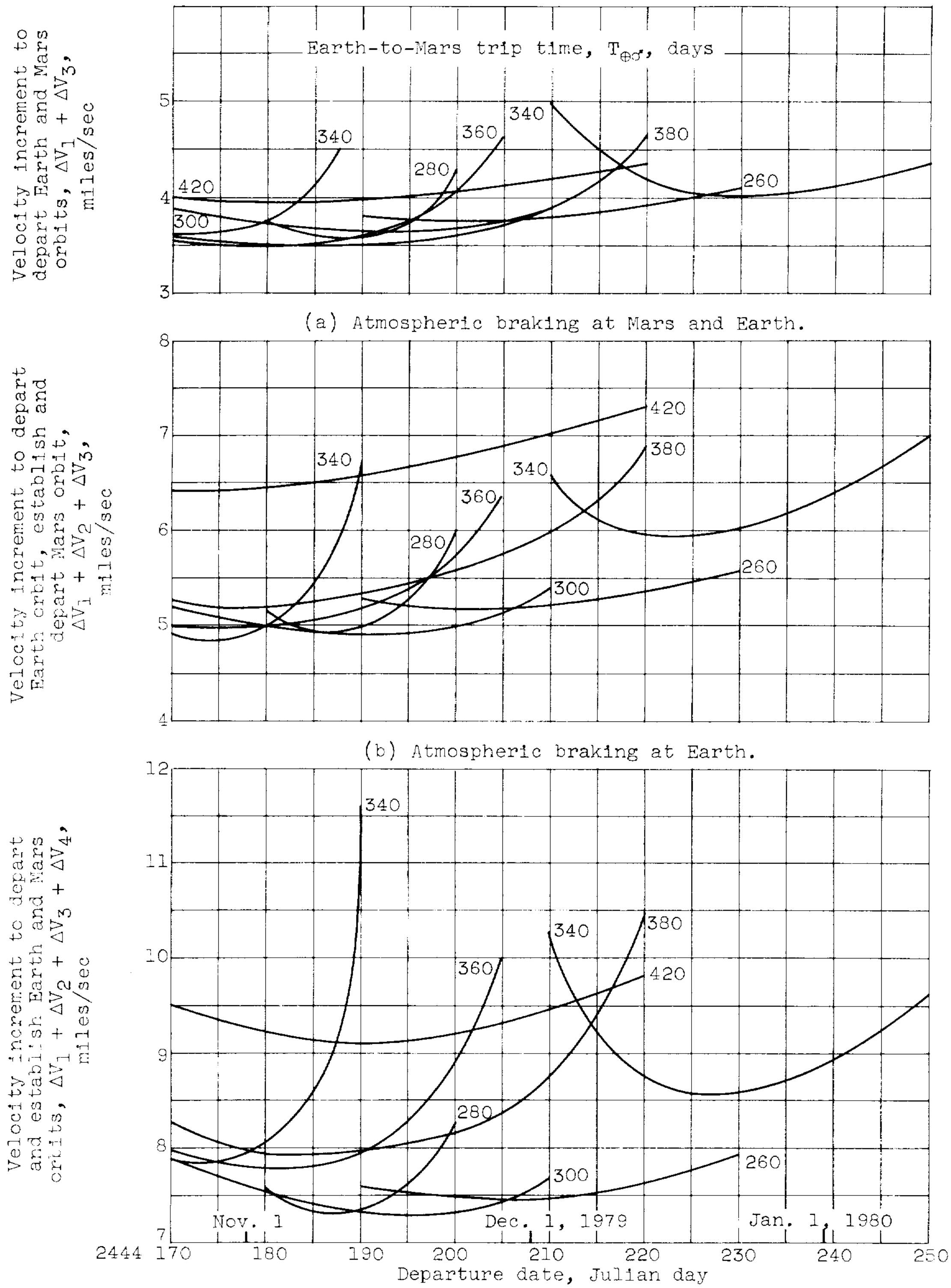


Figure 42. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 310 days.

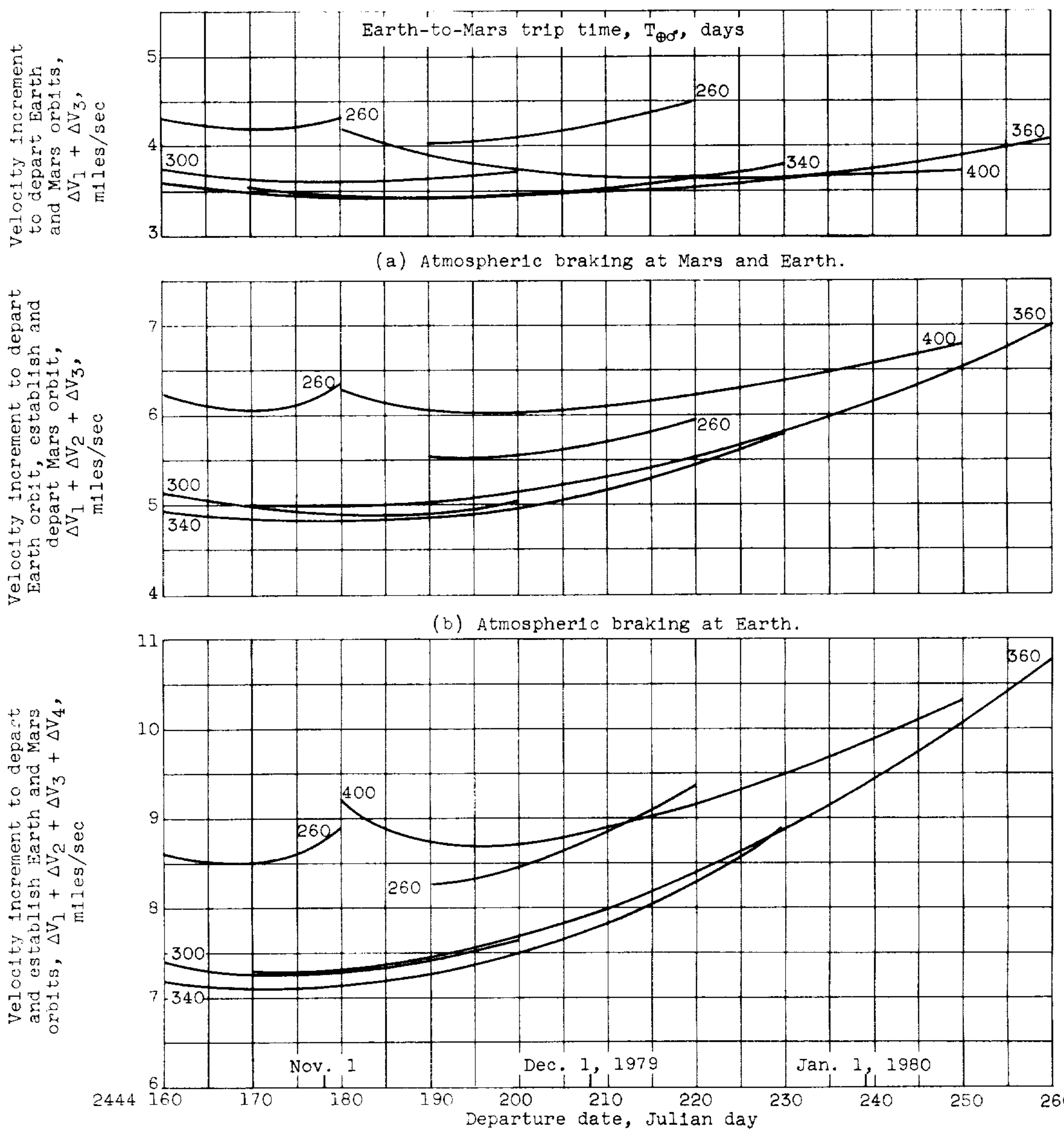


(a) Atmospheric braking at Mars and Earth.

(b) Atmospheric braking at Earth.

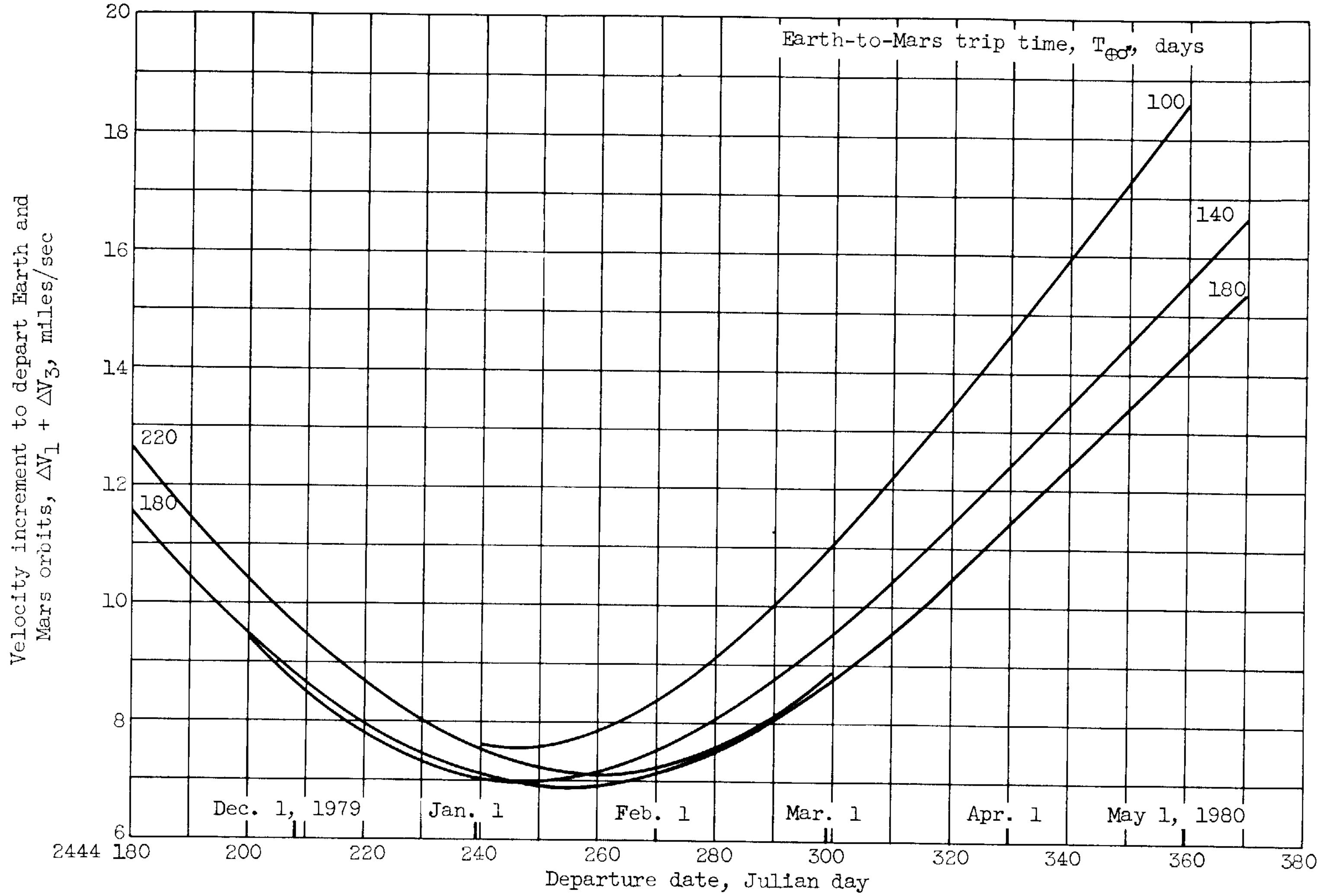
(c) All propulsive braking.

Figure 43. - Velocity increments for 950-day round trip to Mars. Wait time in Mars orbit, 310 days.



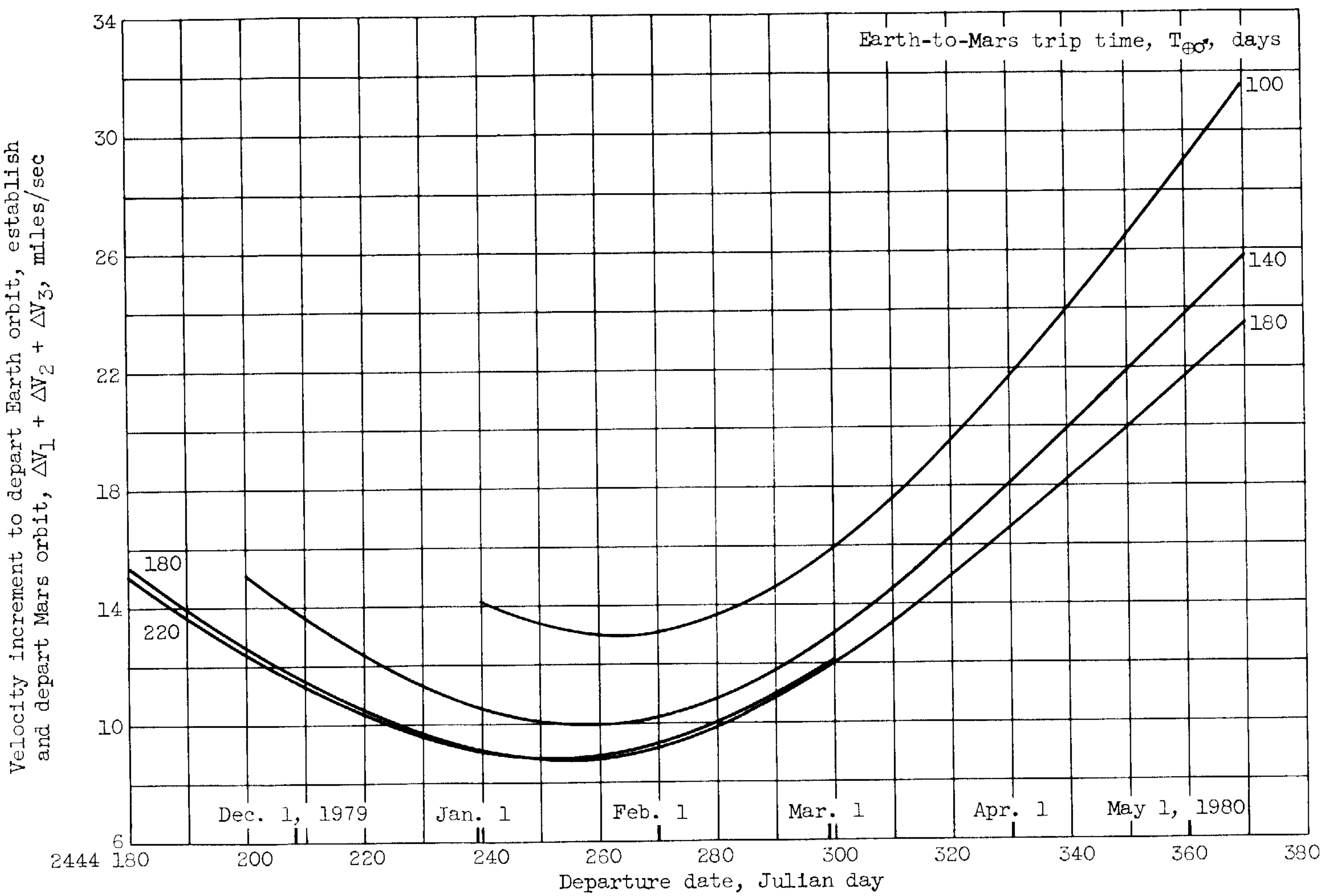
(c) All propulsive braking.

Figure 44. - Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 310 days.



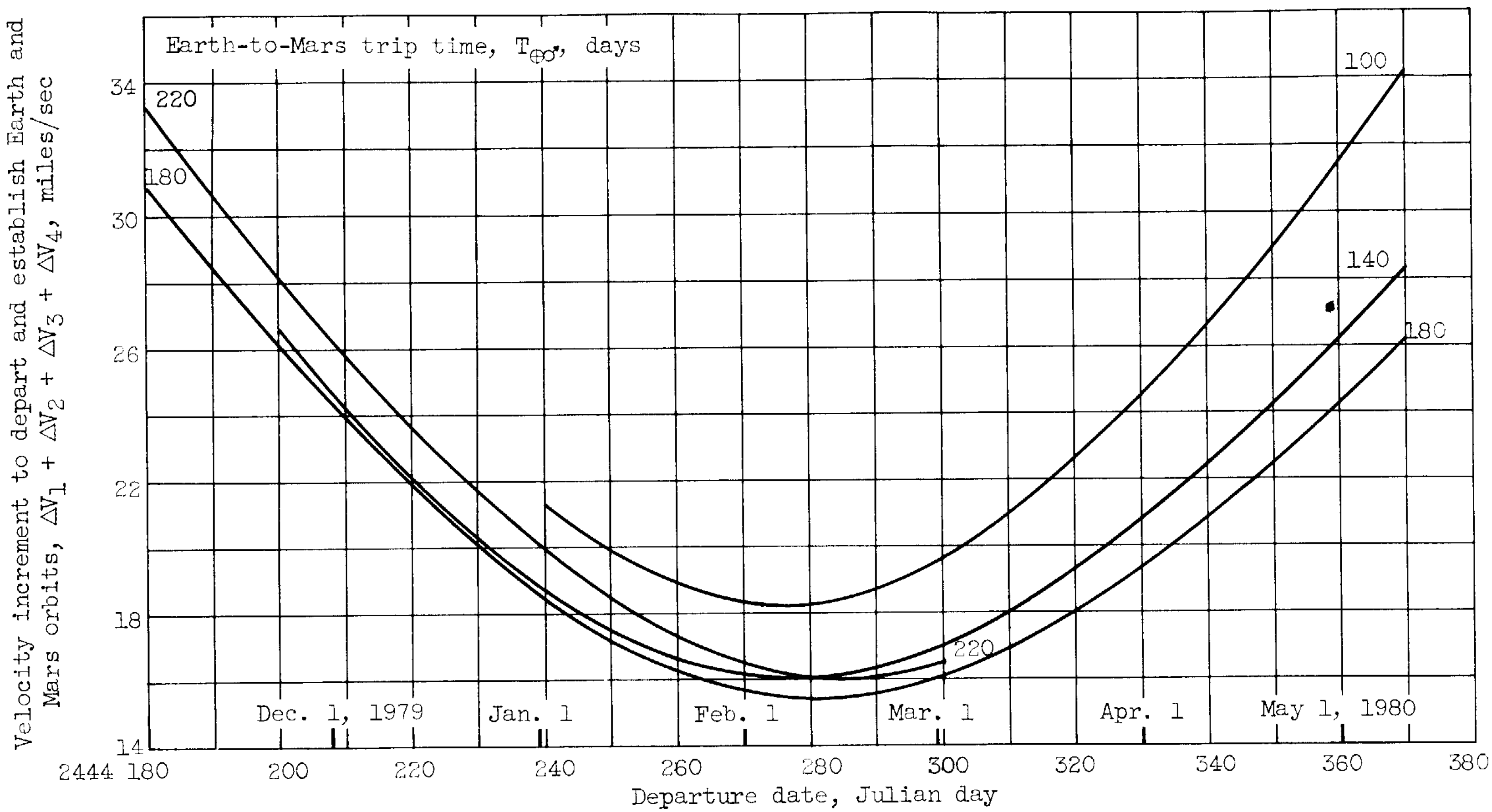
(a) Atmospheric braking at Mars and Earth.

Figure 45. - Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



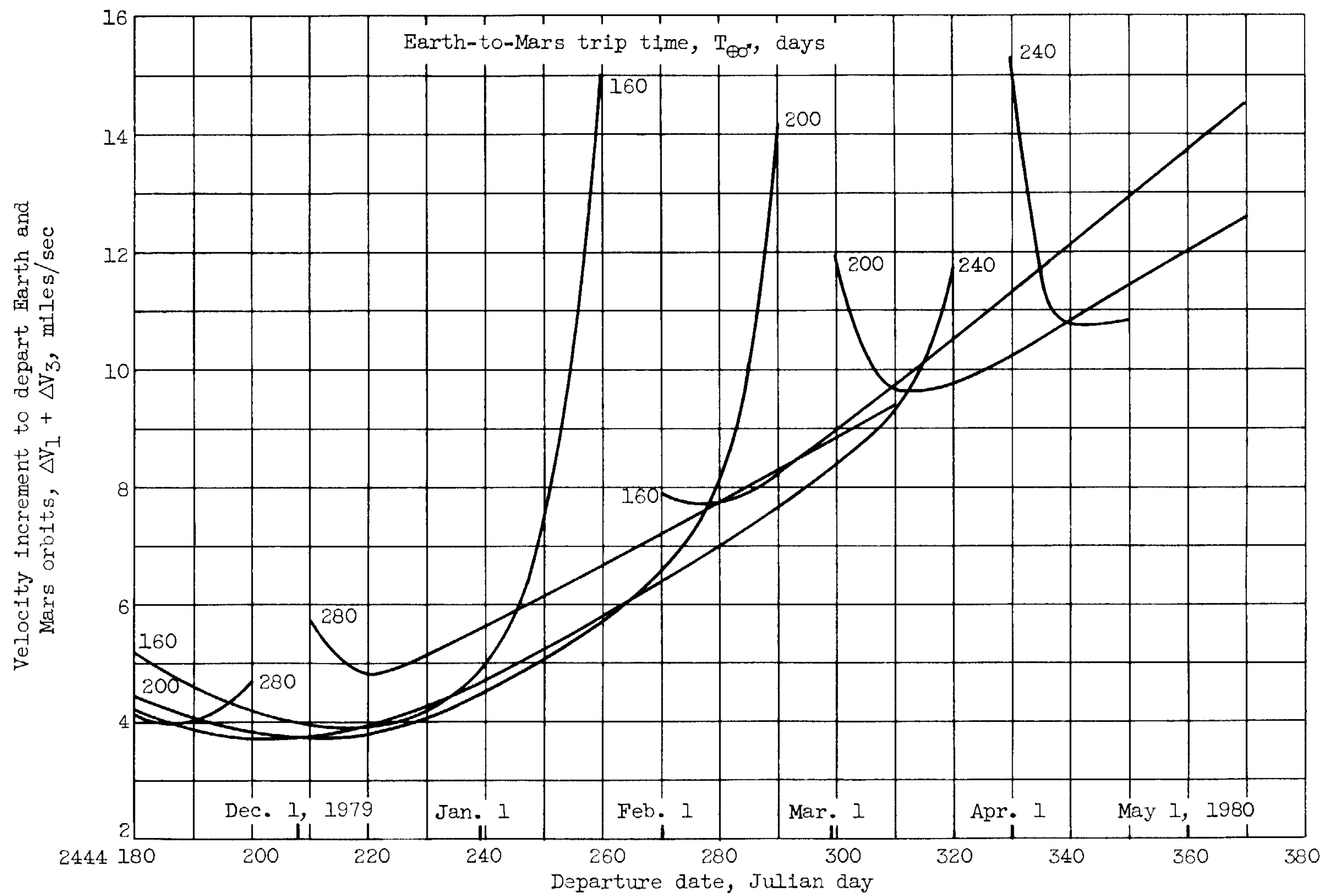
(b) Atmospheric braking at Earth.

Figure 45. - Continued. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



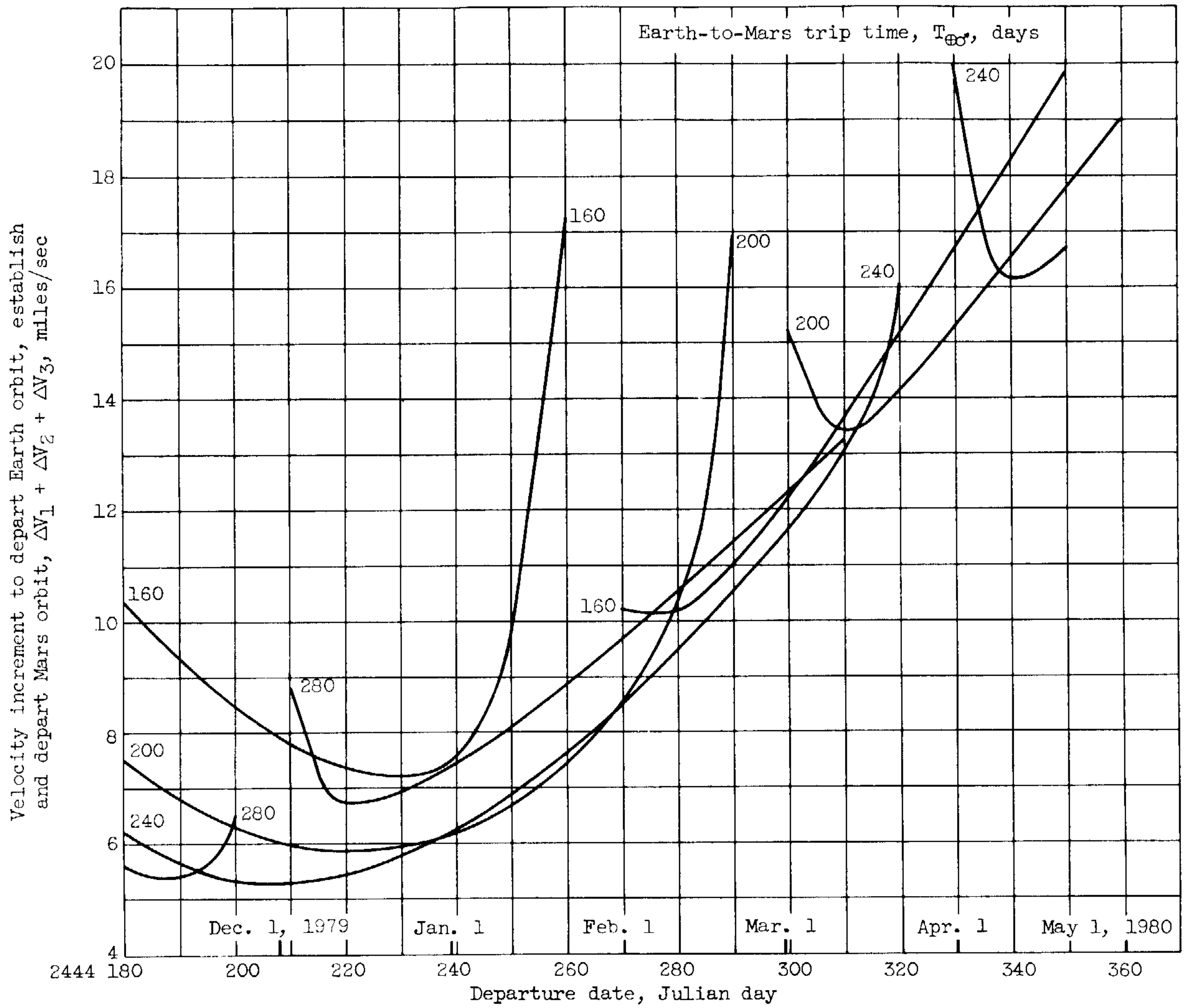
(c) All propulsive braking.

Figure 45. - Concluded. Velocity increments for 800-day round trip to Mars. Wait time in Mars orbit, 450 days.



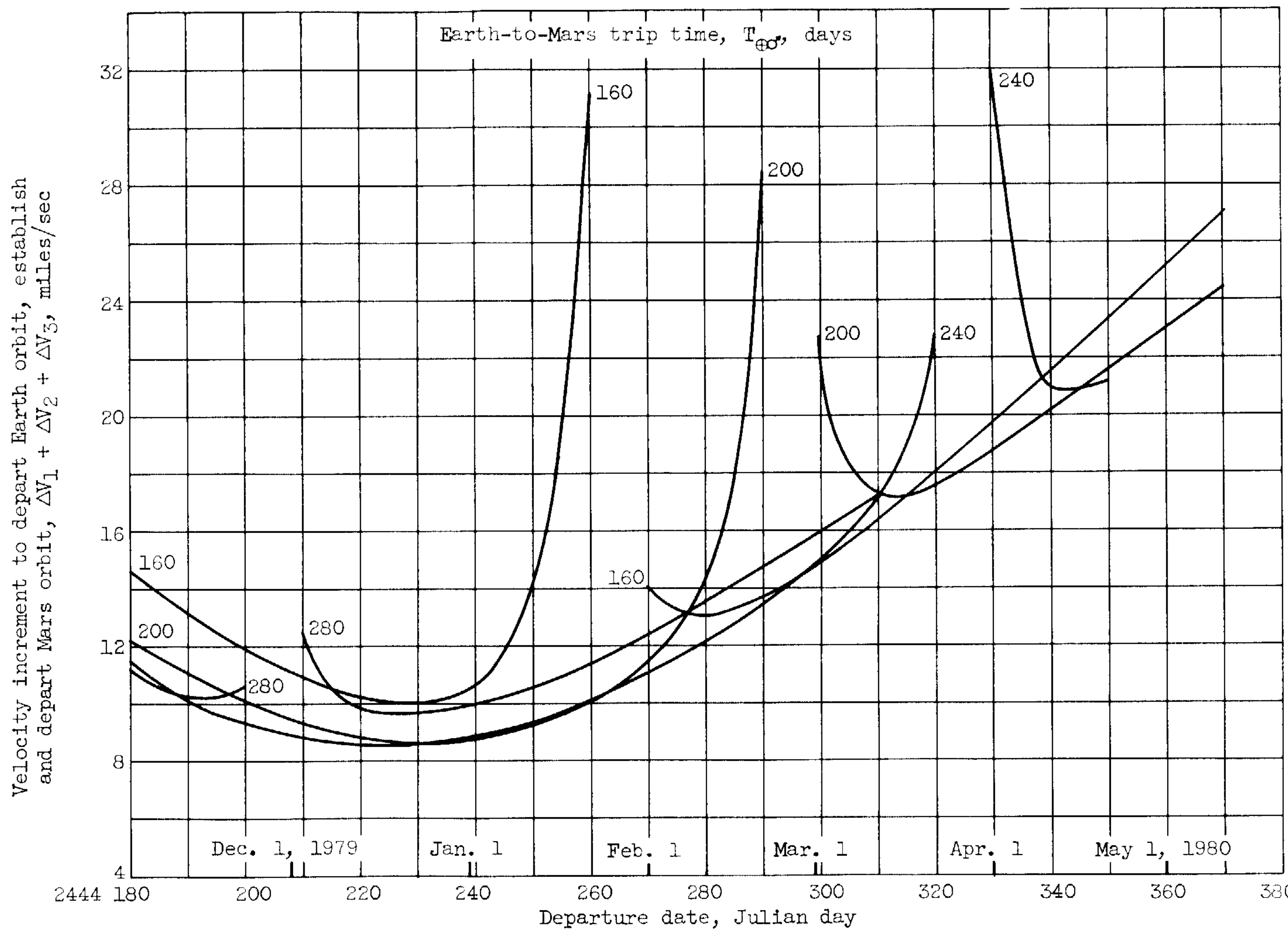
(a) Atmospheric braking at Mars and Earth.

Figure 46. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.



(b) Atmospheric braking at Earth.

Figure 46. - Continued. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.



(c) All propulsive braking.

Figure 46. - Concluded. Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 450 days.

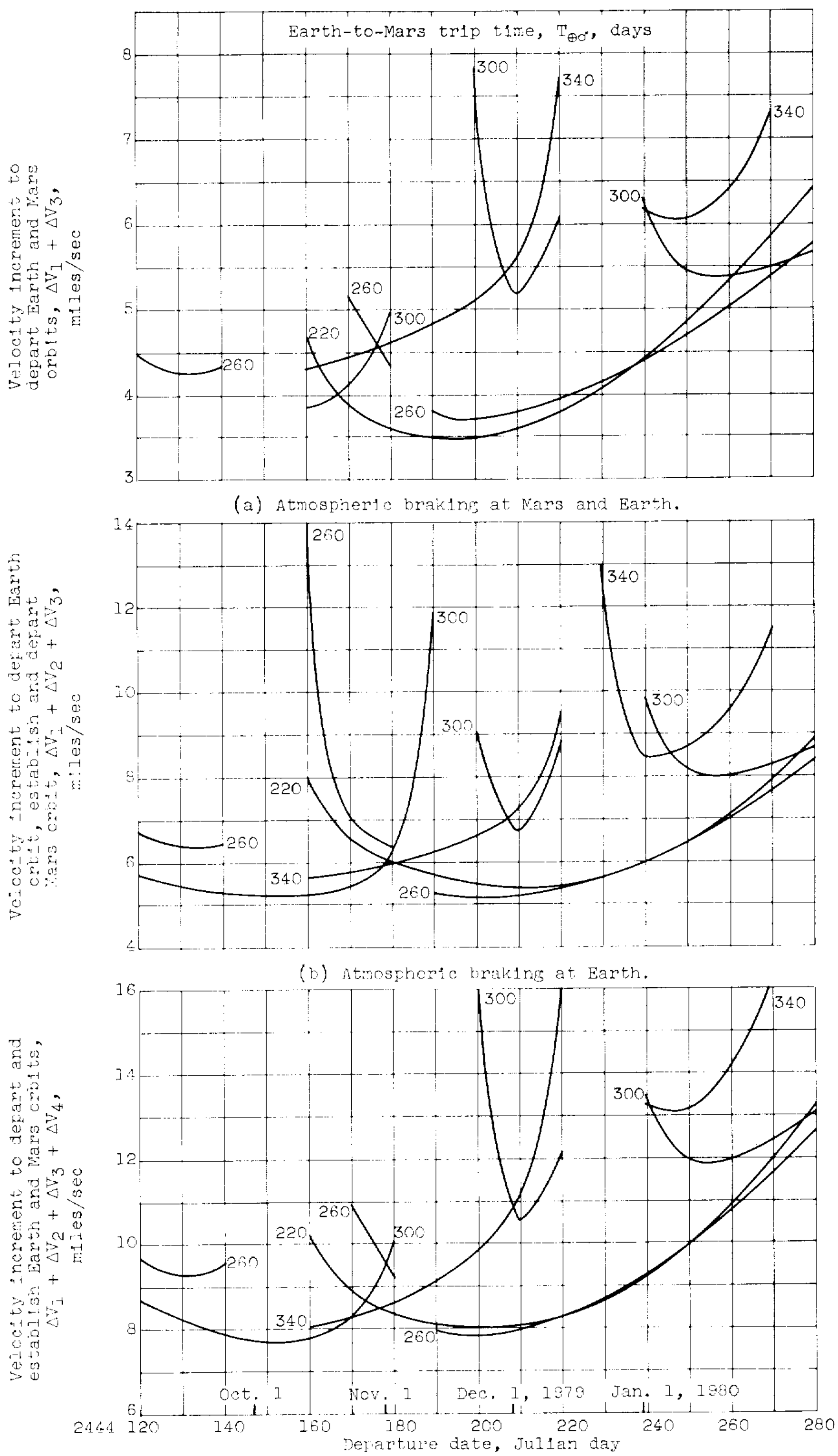


Figure 47. - Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 450 days.

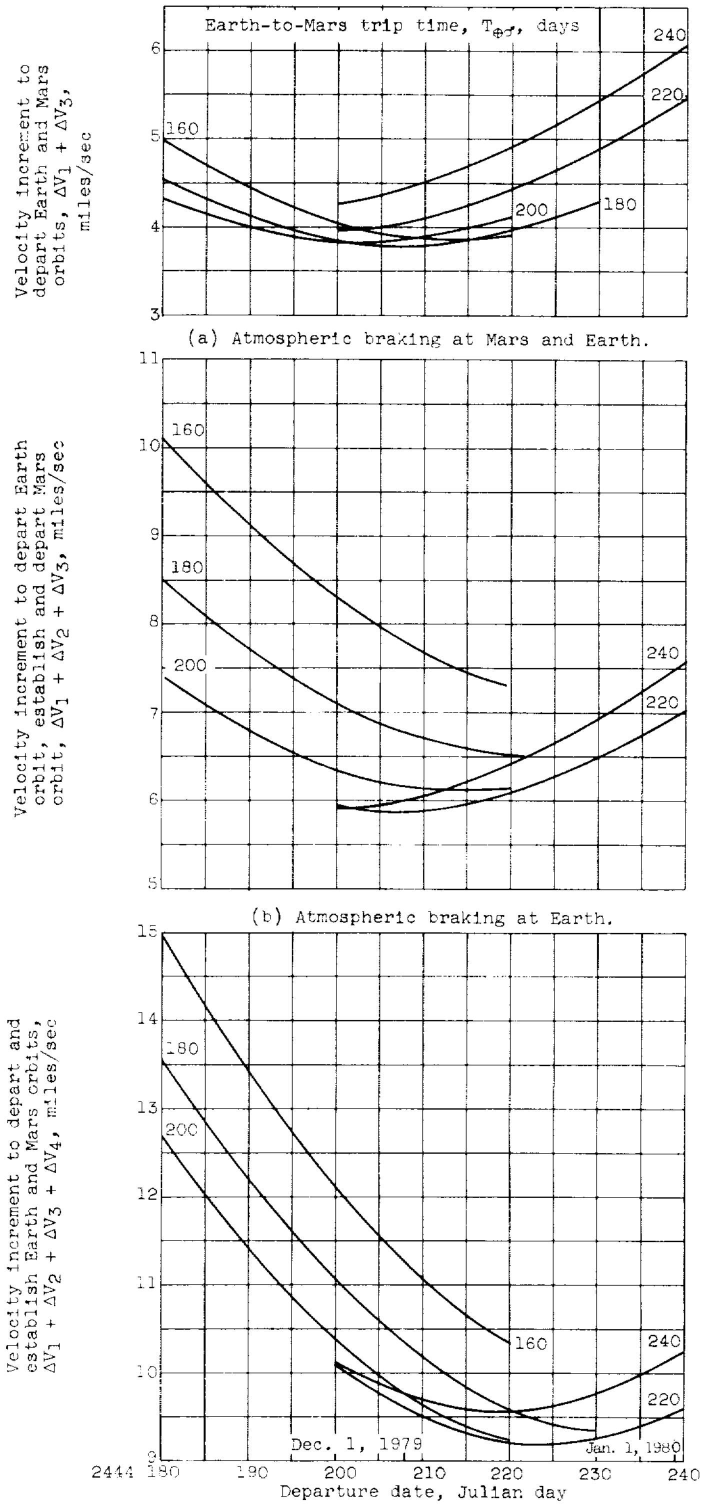
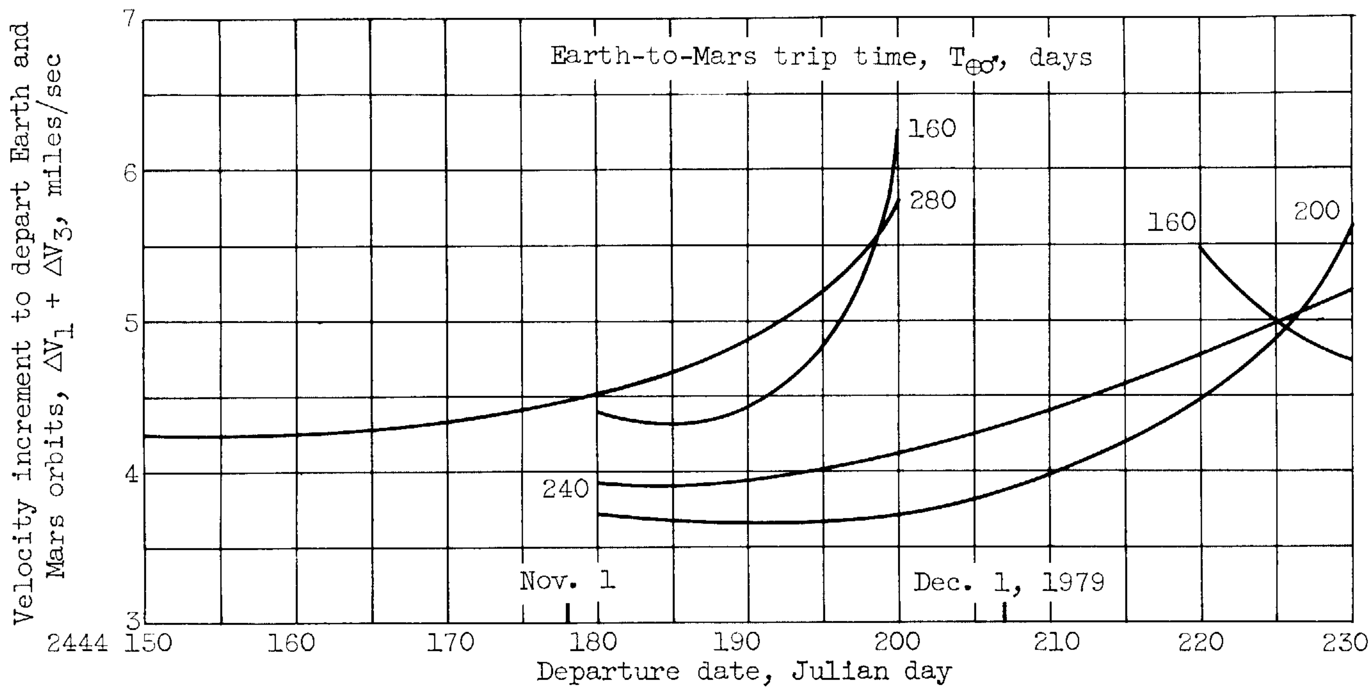
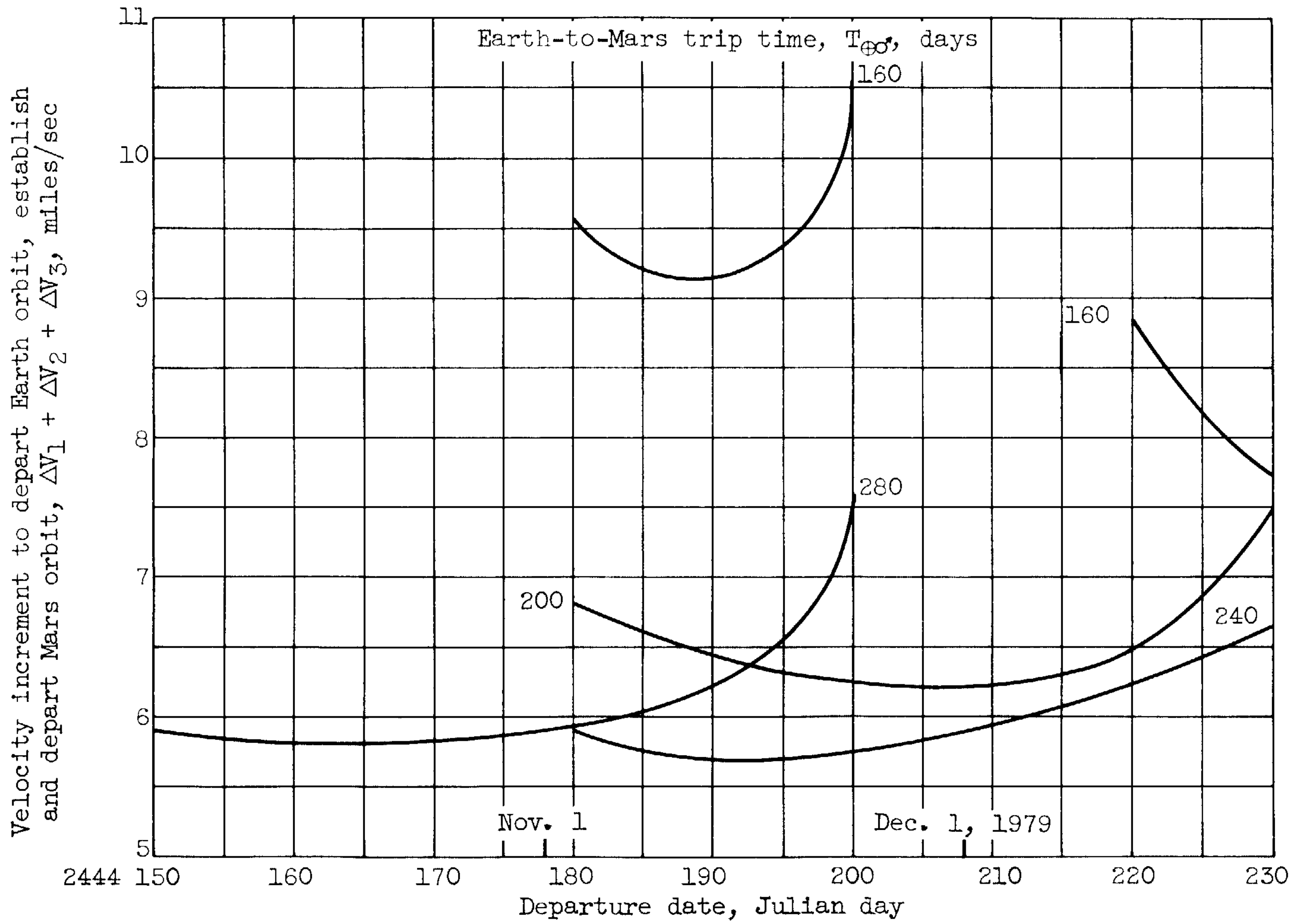


Figure 48. - Velocity increments for 900-day round trip to Mars. Wait time in Mars orbit, 500 days.



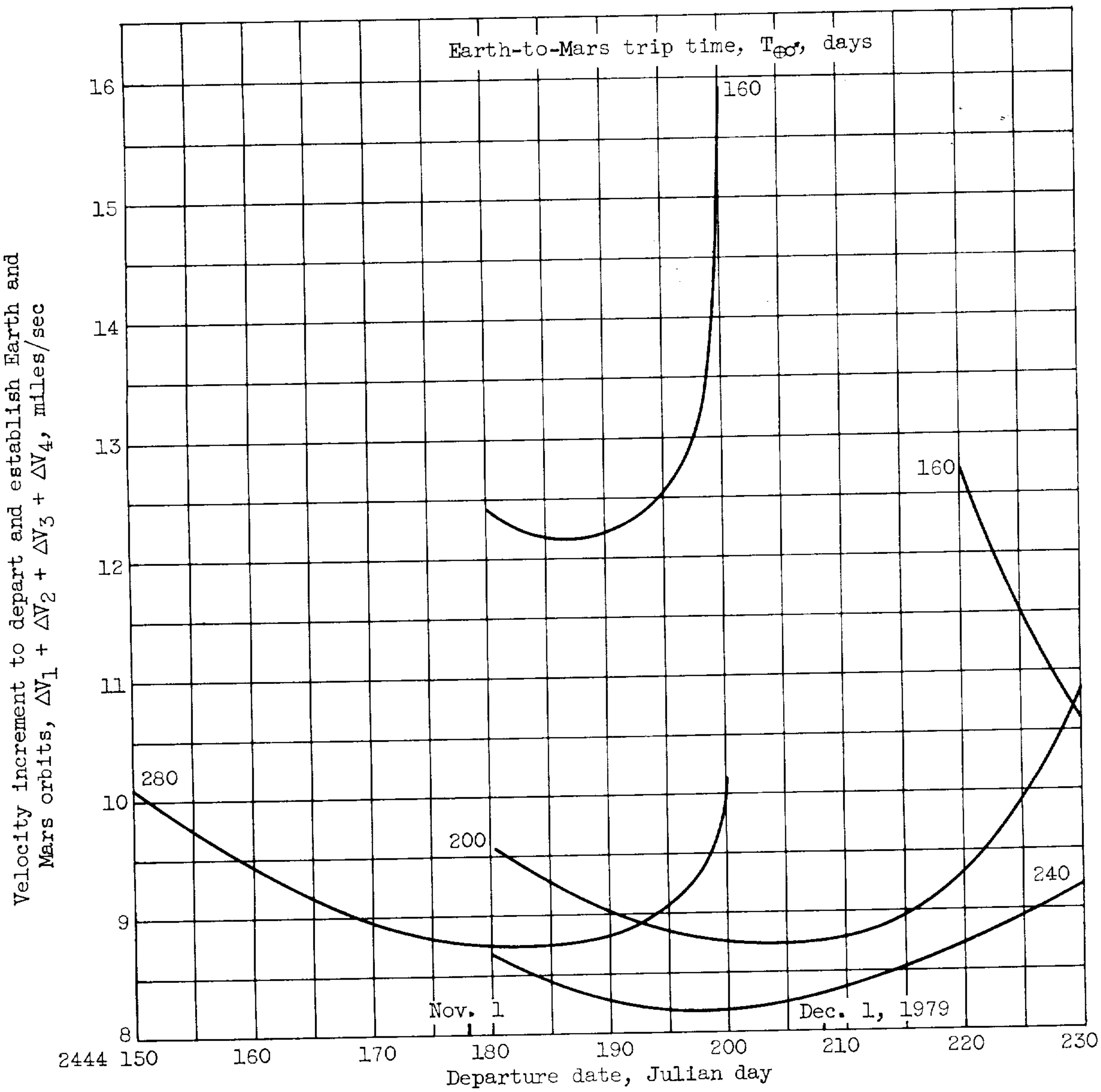
(a) Atmospheric braking at Mars and Earth.

Figure 49. - Velocity increments for 950-day round trip to Mars. Wait time in Mars orbit, 500 days.



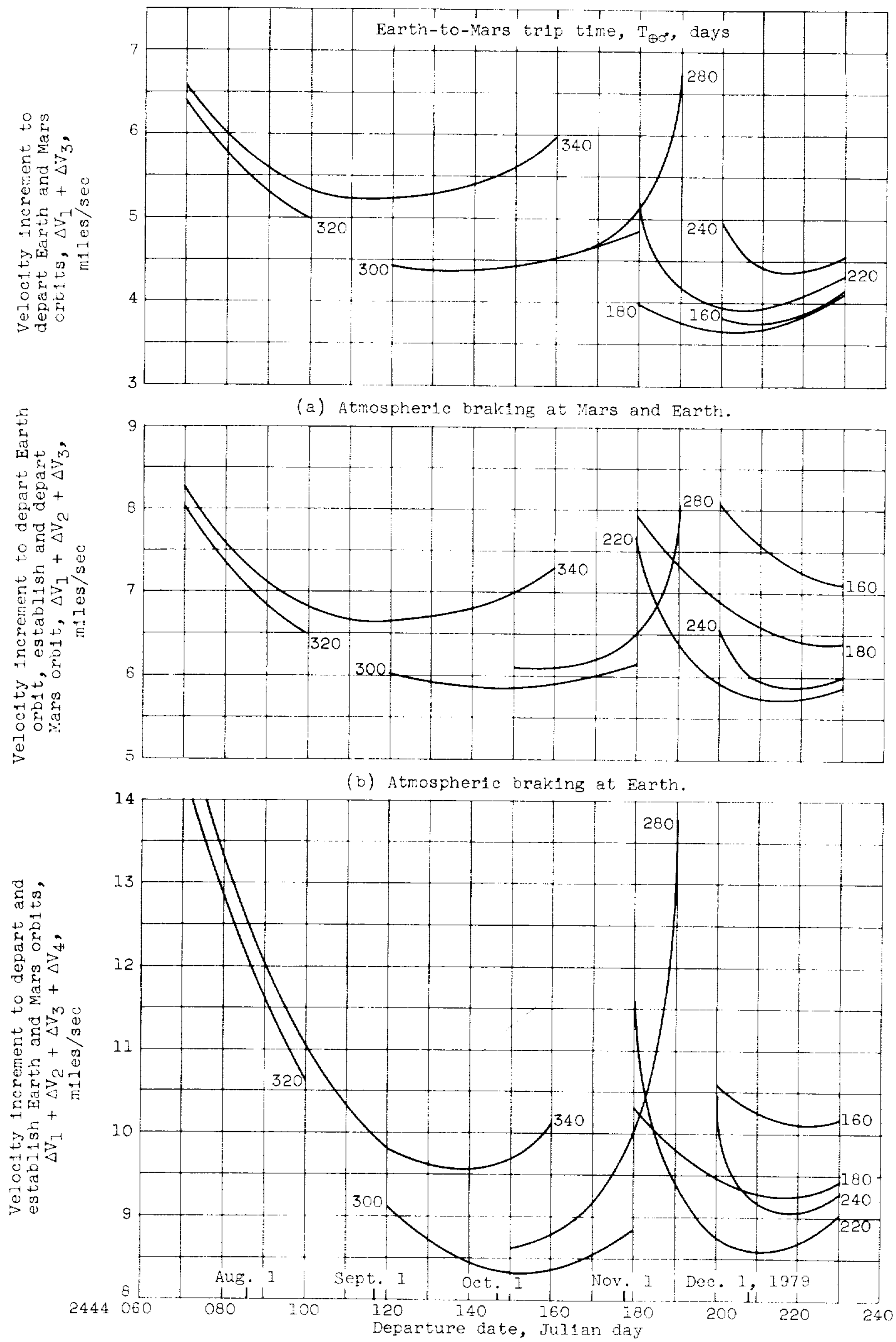
(b) Atmospheric braking at Earth.

Figure 49. - Continued. Velocity increments for 950-day round trip to Mars. Wait time in Mars orbit, 500 days.



(c) All propulsive braking.

Figure 49. - Concluded. Velocity increments for 950-day round trip to Mars. Wait time in Mars orbit, 500 days.

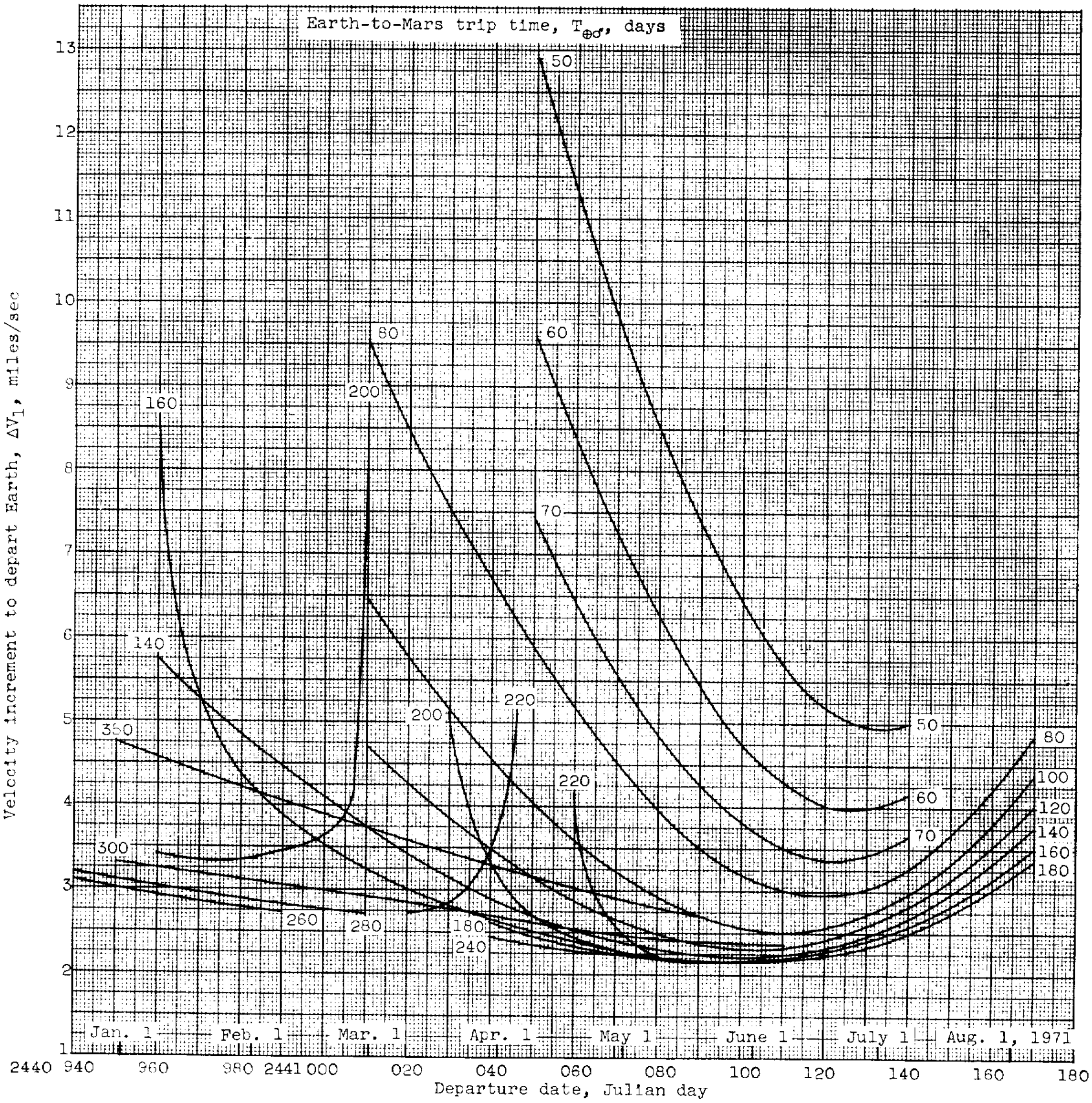


(a) Atmospheric braking at Mars and Earth.

(b) Atmospheric braking at Earth.

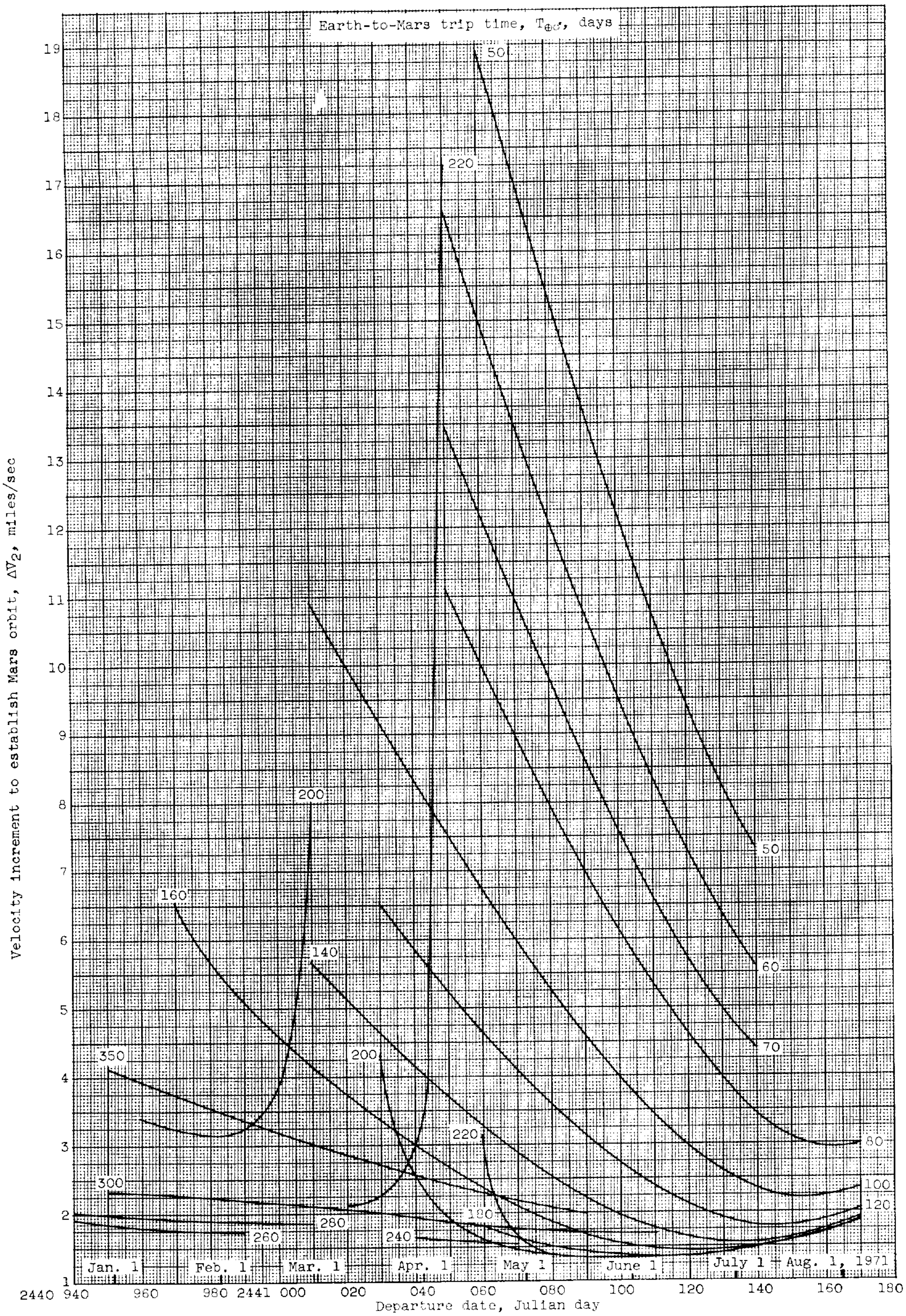
(c) All propulsive braking.

Figure 50. - Velocity increments for 1000-day round trip to Mars. Wait time in Mars orbit, 500 days.



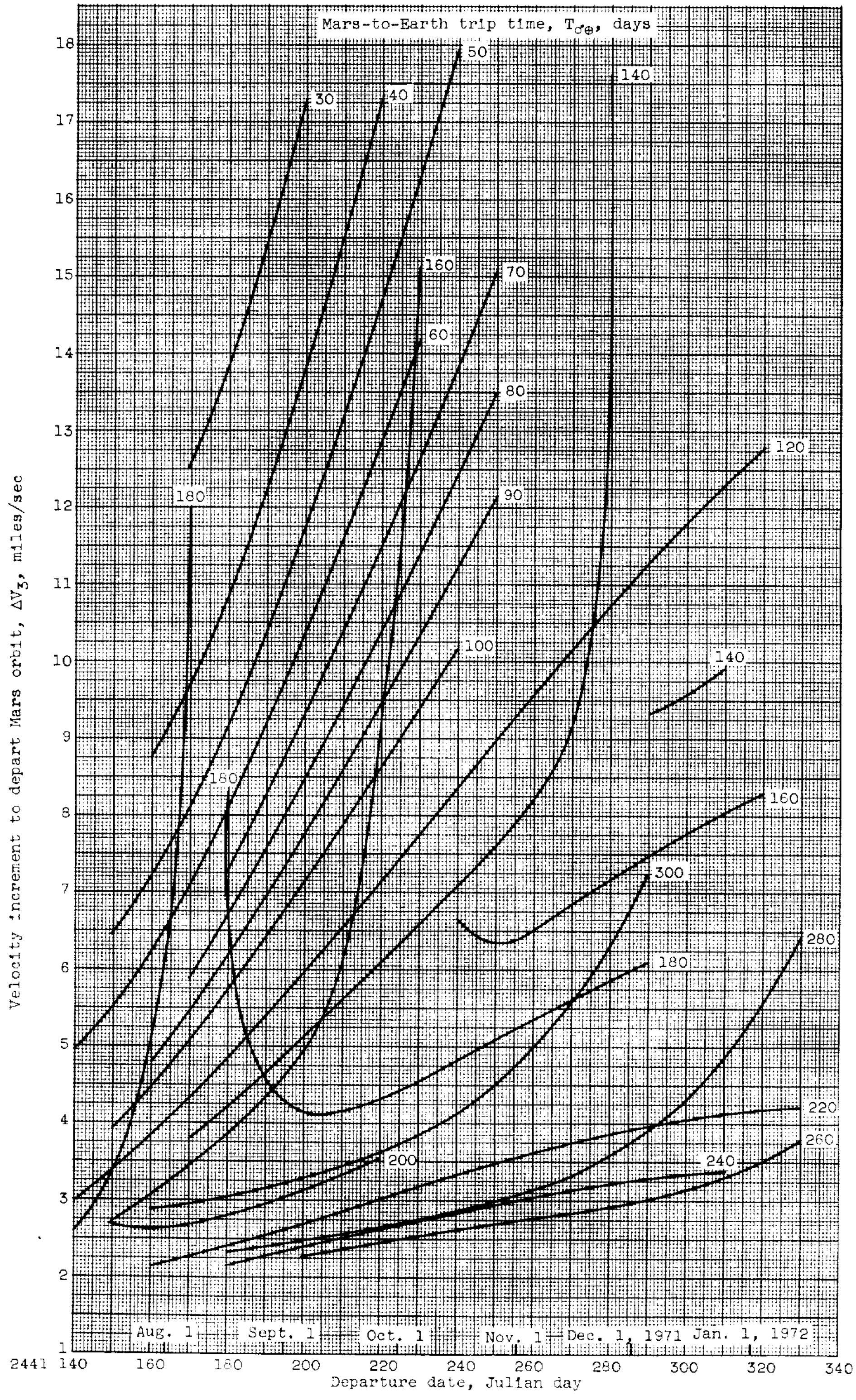
(a) Depart Earth.

Figure 51. - Velocity increments for round-trip missions between Earth and Mars, 1970-71.



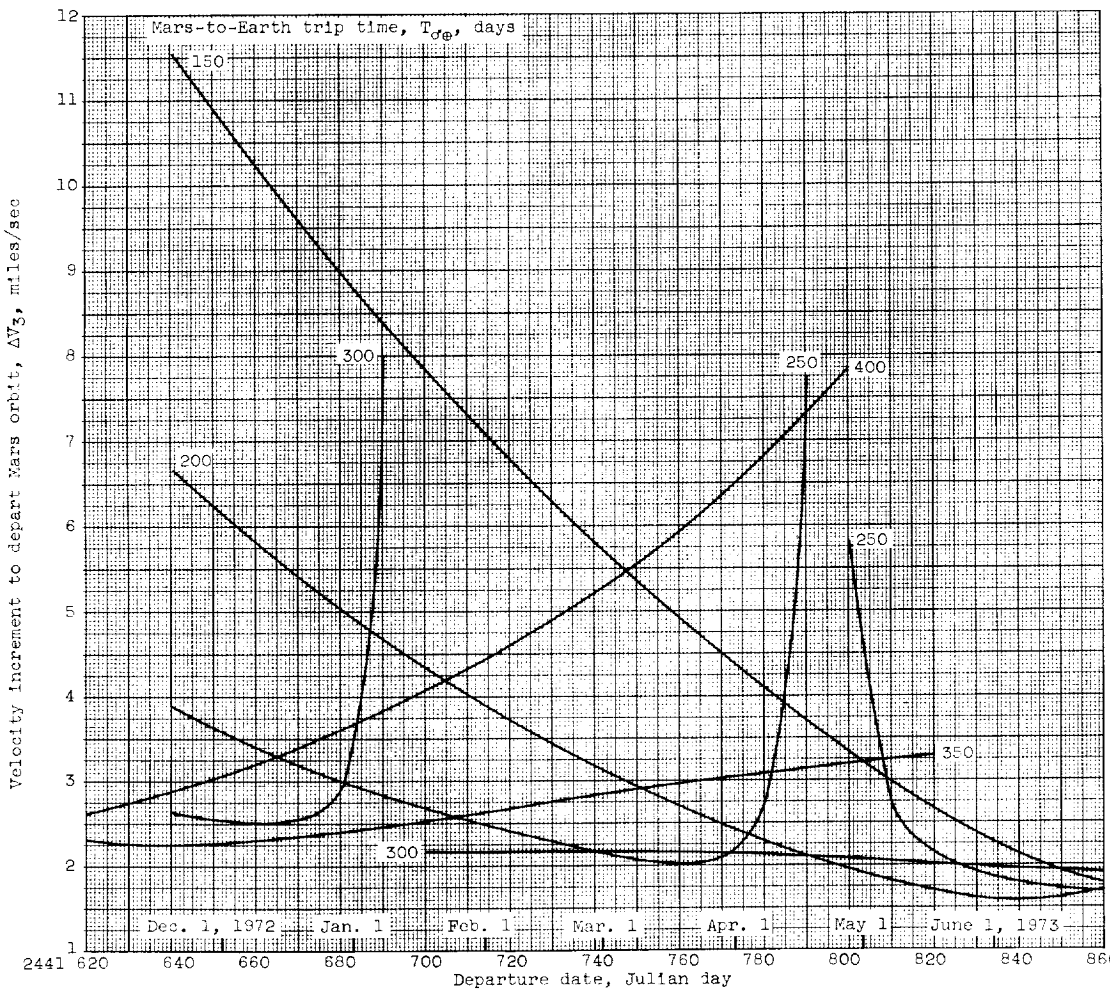
(b) Arrive Mars.

Figure 51. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1970-71.



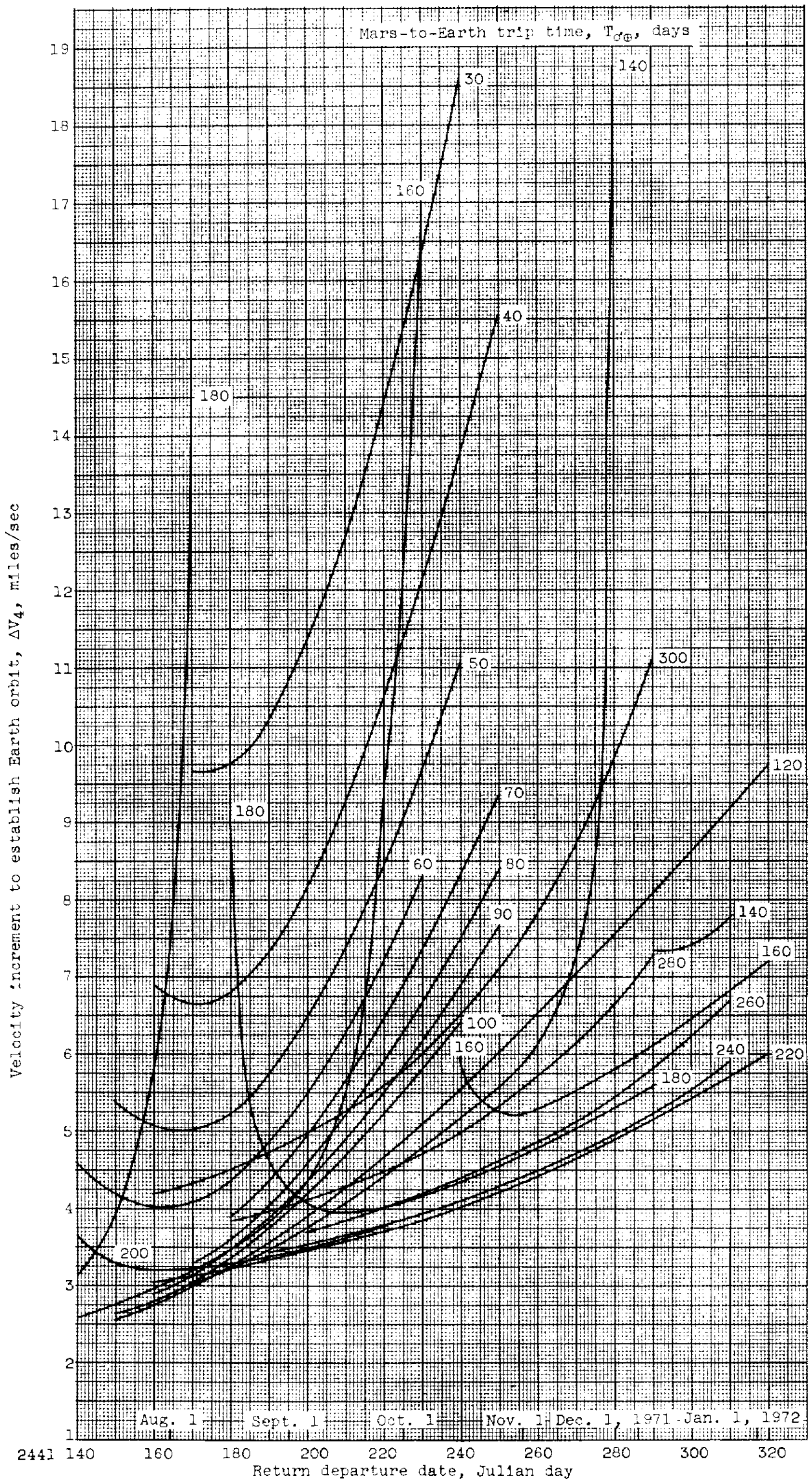
(c) Depart Mars.

Figure 51. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1970-71.



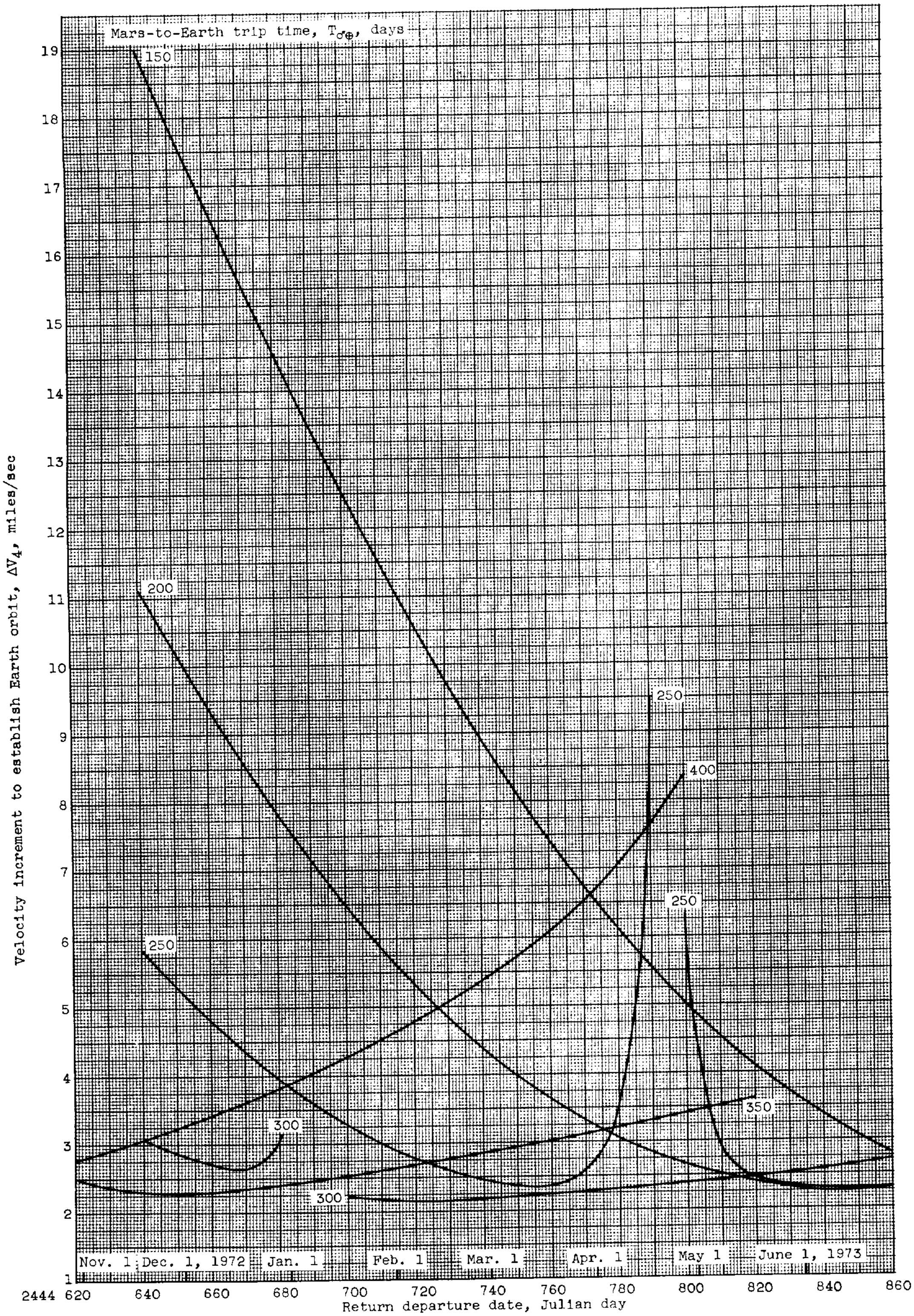
(c) Concluded. Depart Mars.

Figure 51. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1970-71.



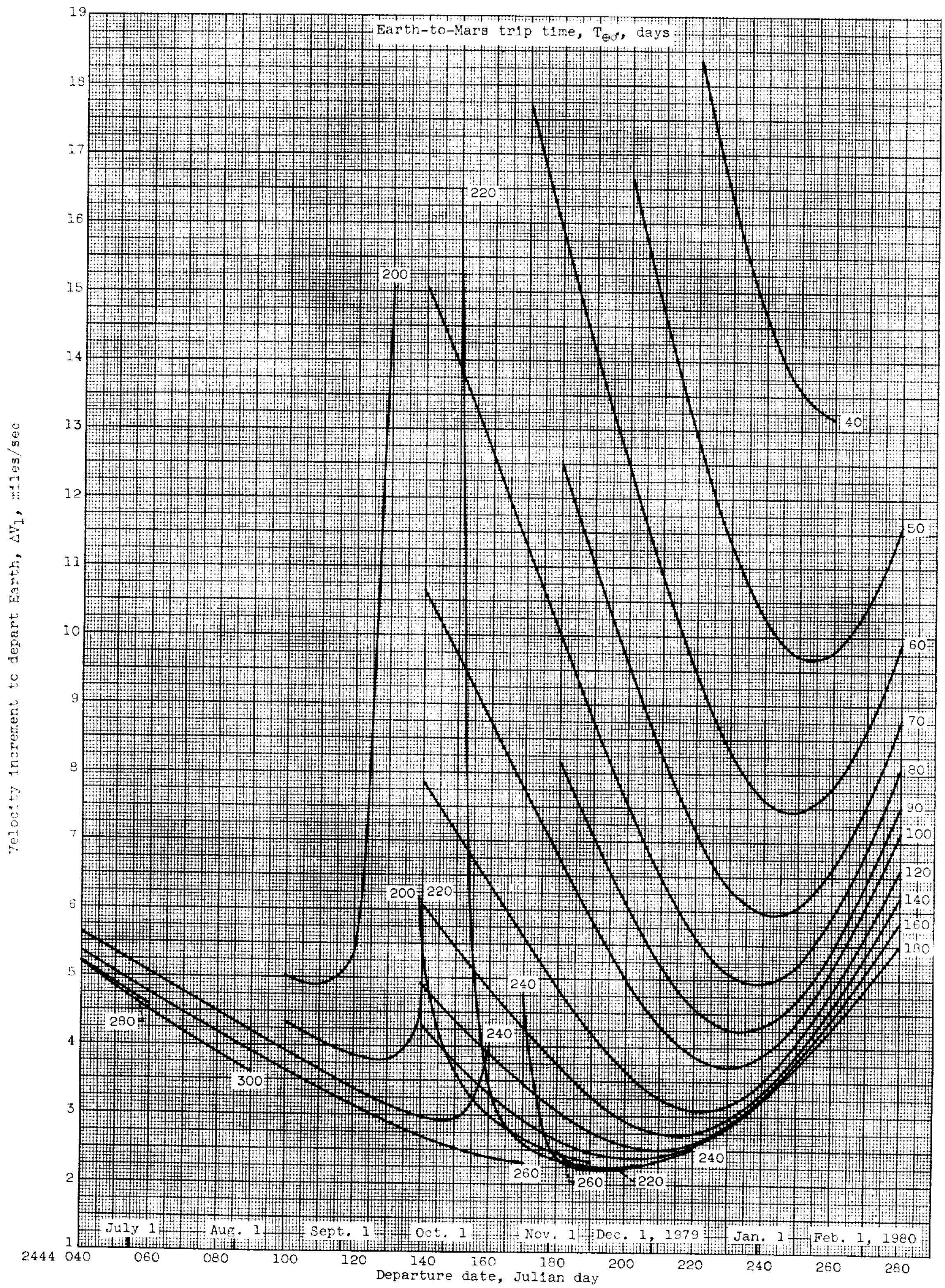
(d) Arrive Earth.

Figure 51. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1970-71.



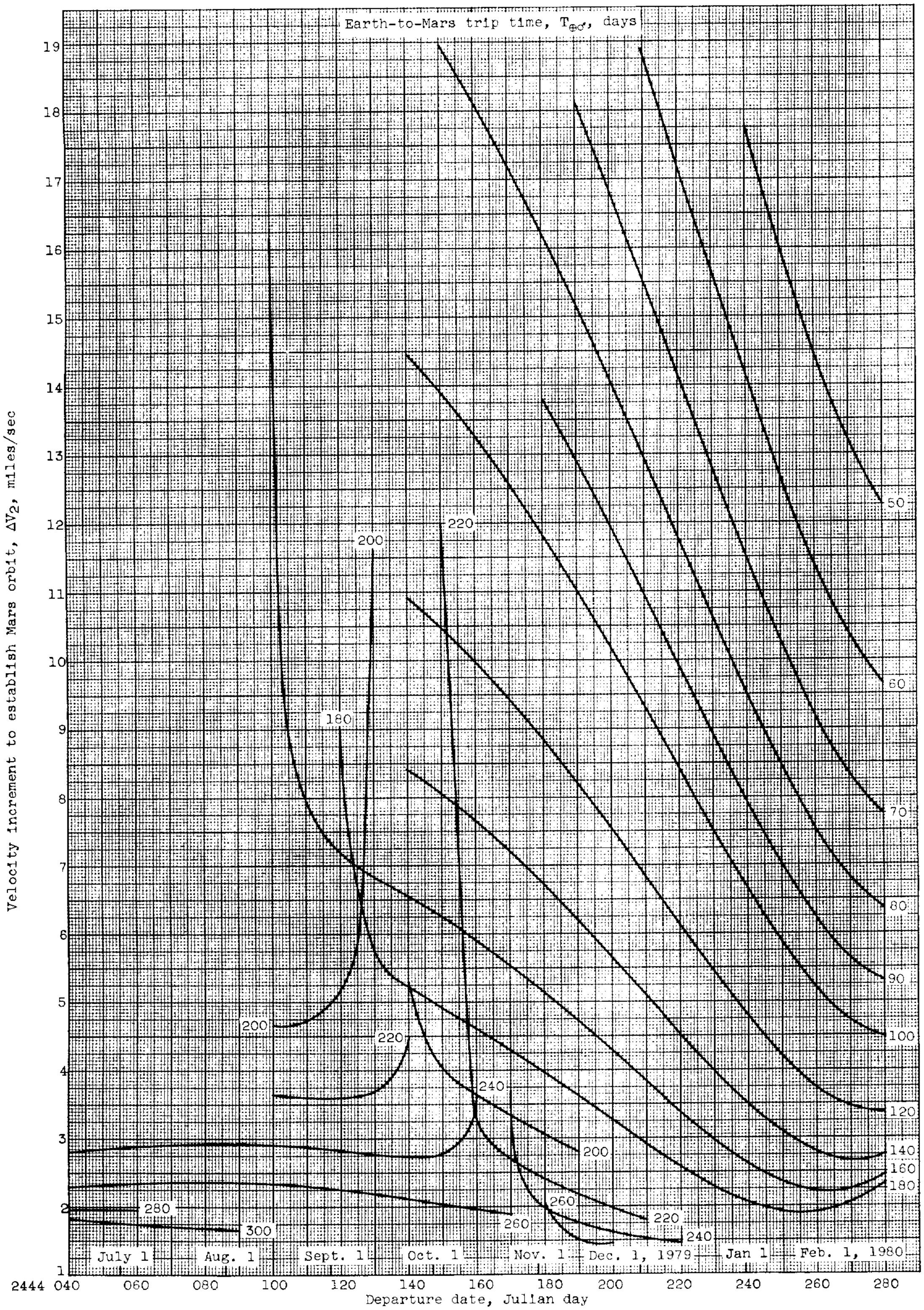
(d) Concluded. Arrive Earth.

Figure 51. - Concluded. Velocity increments for round-trip missions between Earth and Mars, 1970-71.



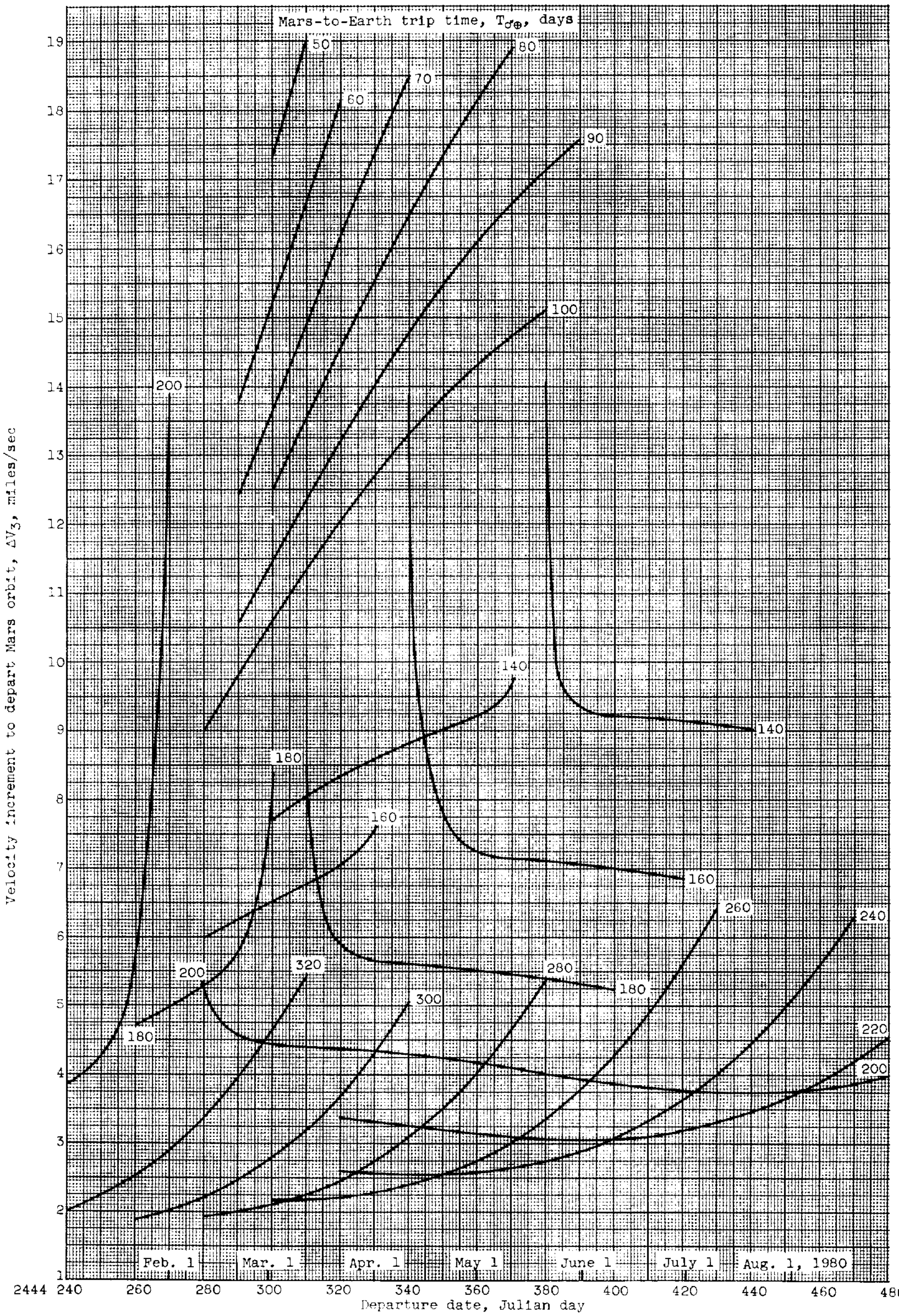
(a) Depart Earth.

Figure 52. - Velocity increments for round-trip missions between Earth and Mars, 1979-80.



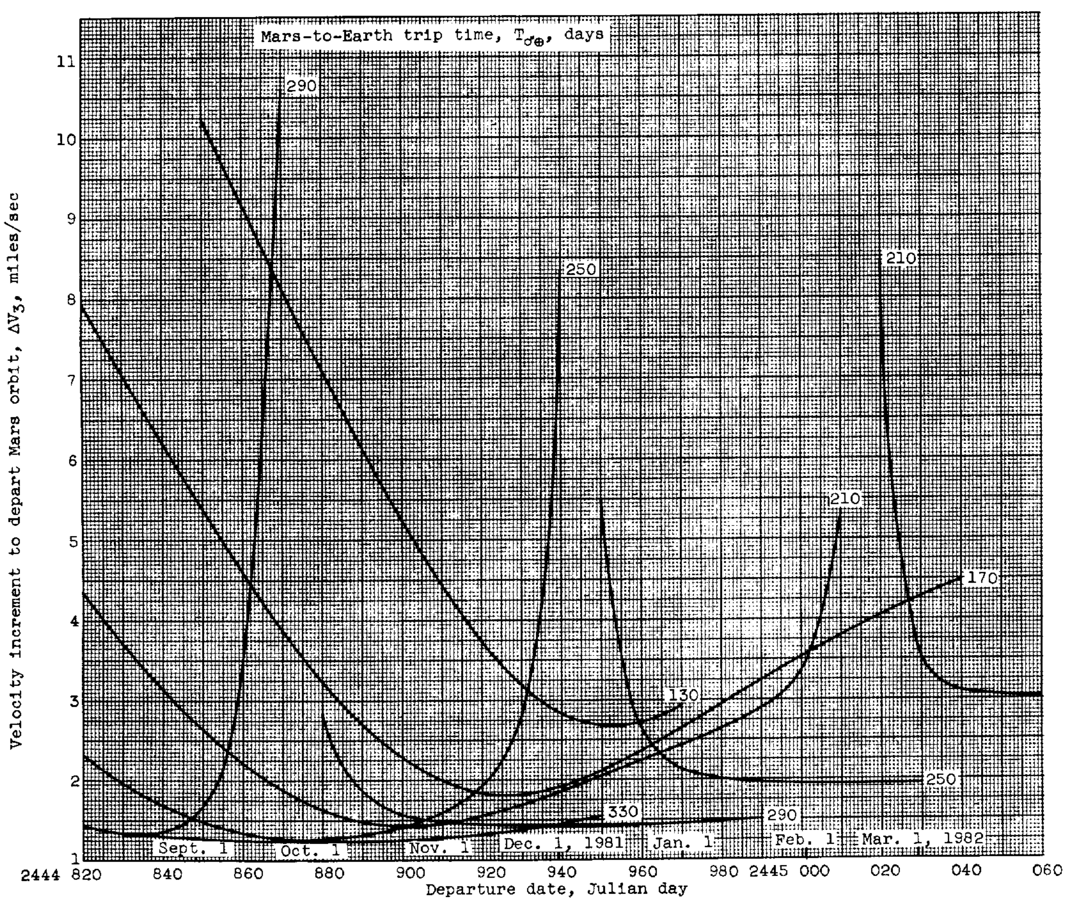
(b) Arrive Mars.

Figure 52. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1979-80.



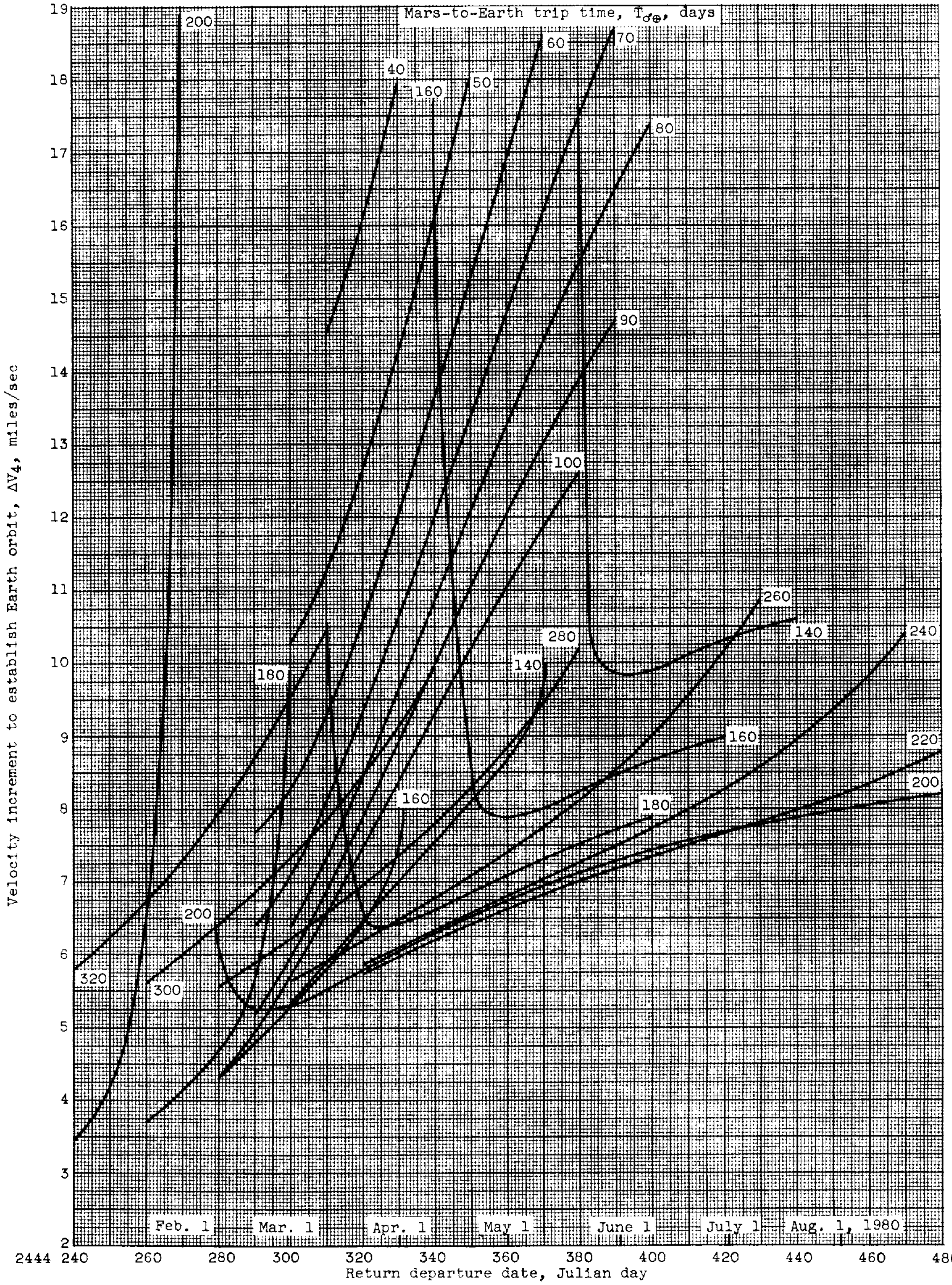
(e) Depart Mars.

Figure 52. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1979-80.



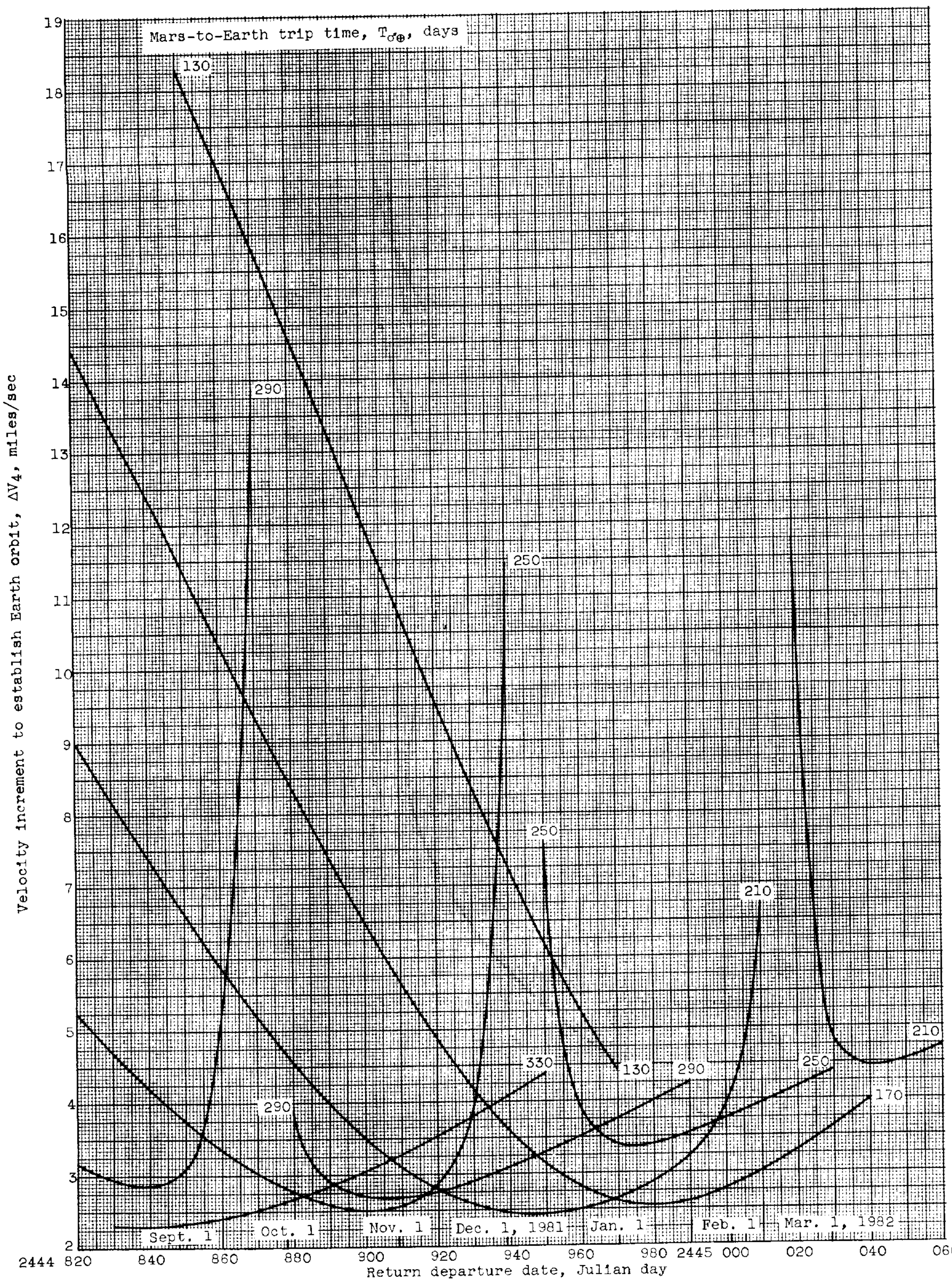
(c) Concluded. Depart Mars.

Figure 52. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1979-80.



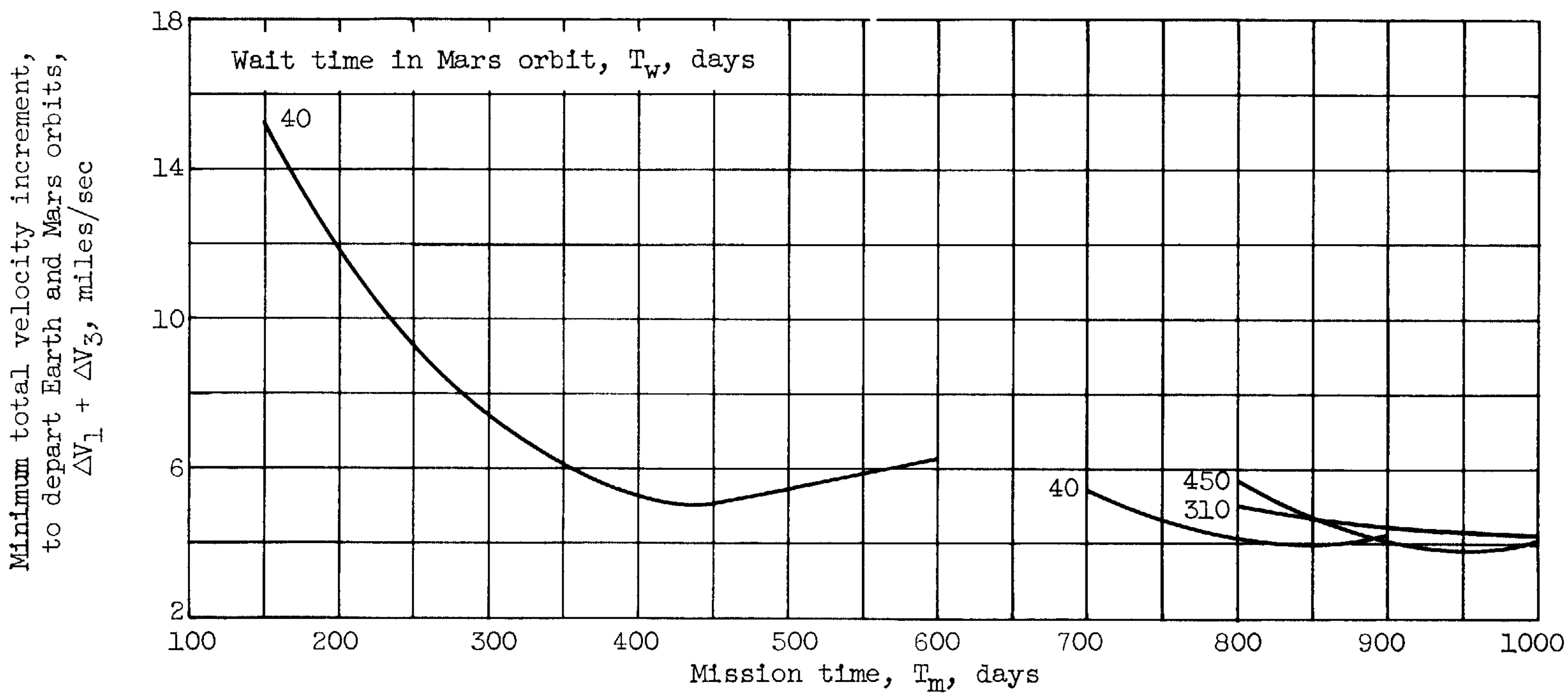
(d) Arrive Earth.

Figure 52. - Continued. Velocity increments for round-trip missions between Earth and Mars, 1979-80.



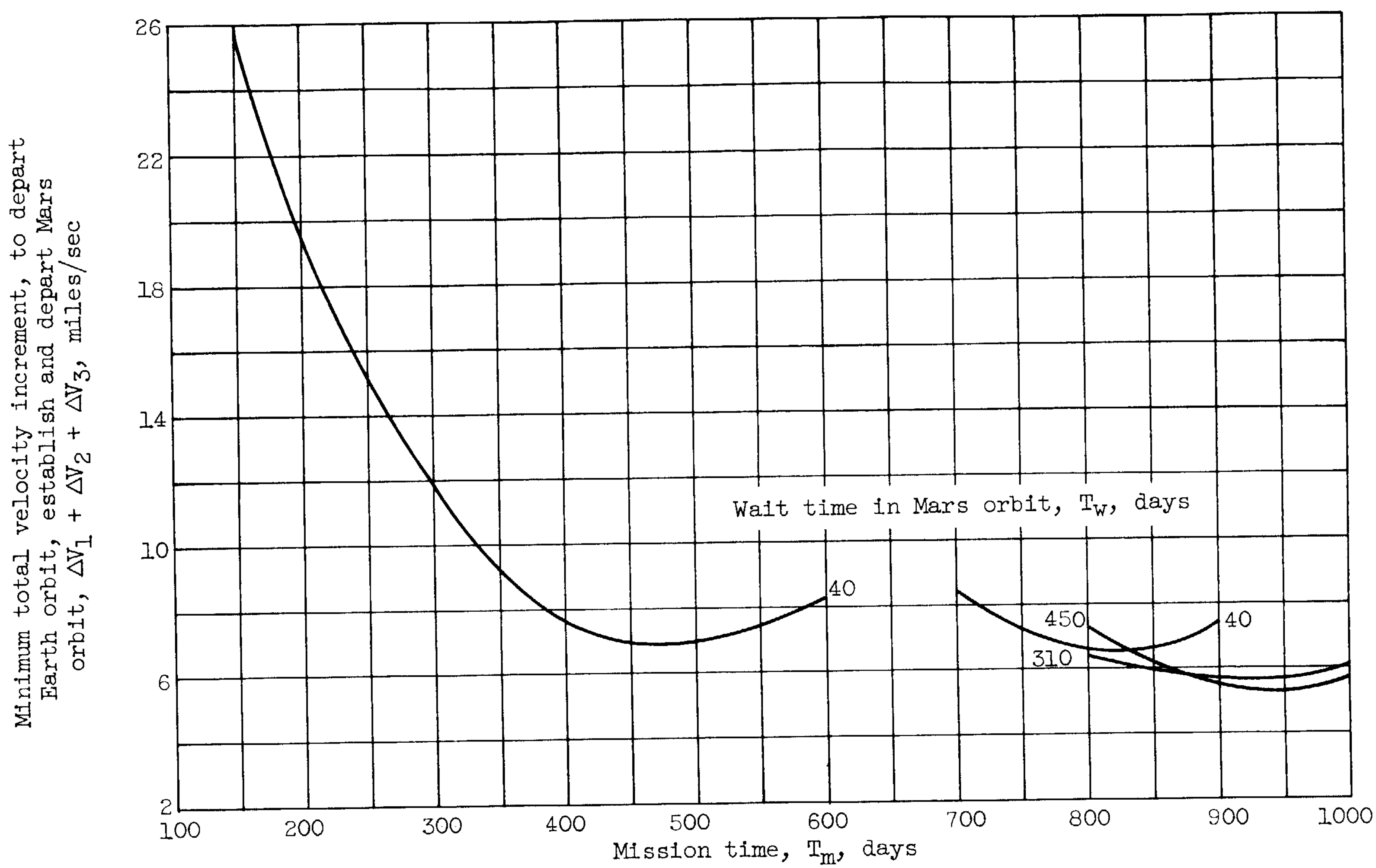
(d) Concluded. Arrive Earth.

Figure 52. - Concluded. Velocity increments for round-trip missions between Earth and Mars, 1979-80.



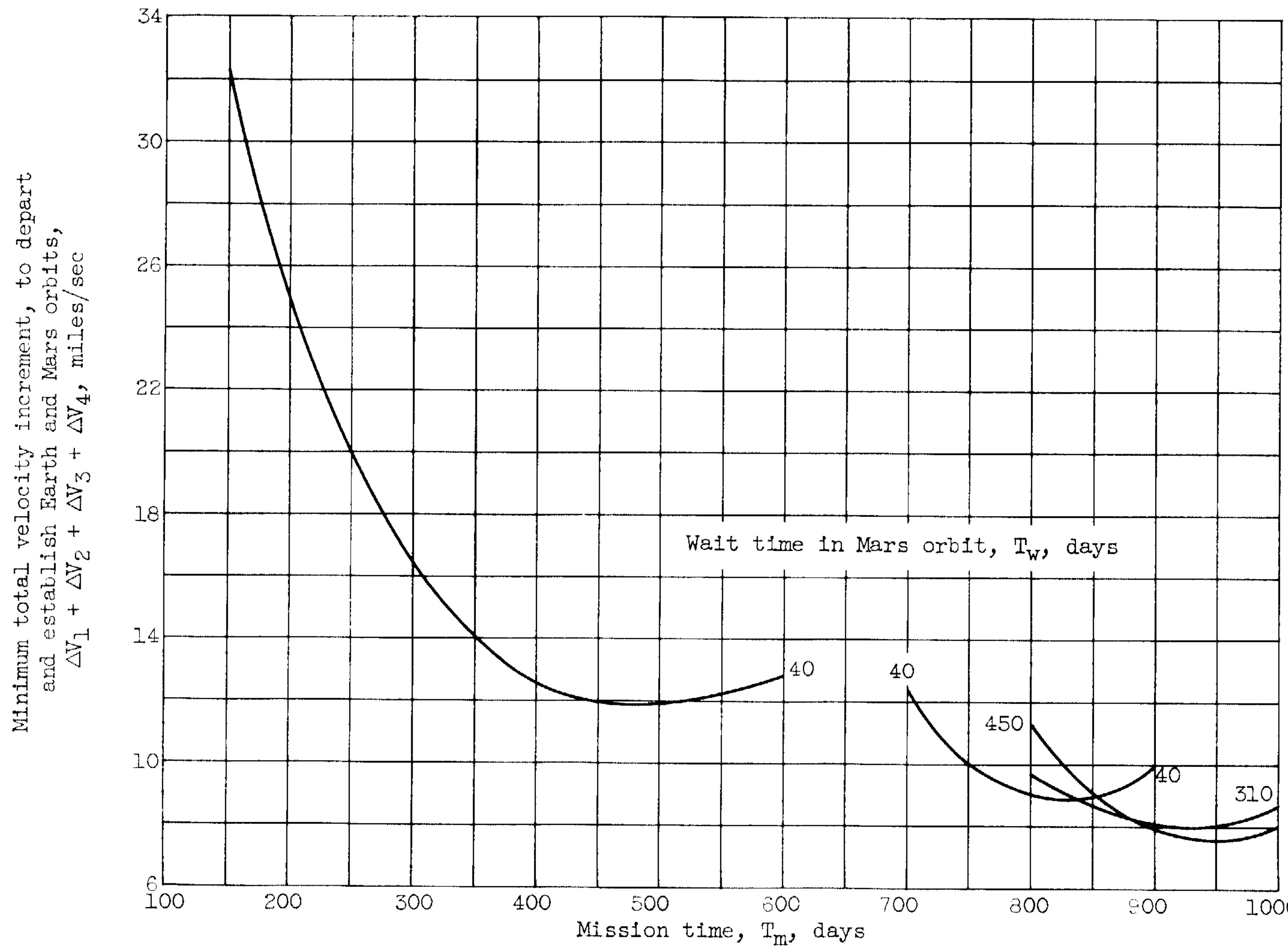
(a) Atmospheric braking at Mars and Earth.

Figure 53. - Minimum total velocity increments required for round trips to Mars. Departure dates, 1970-71.



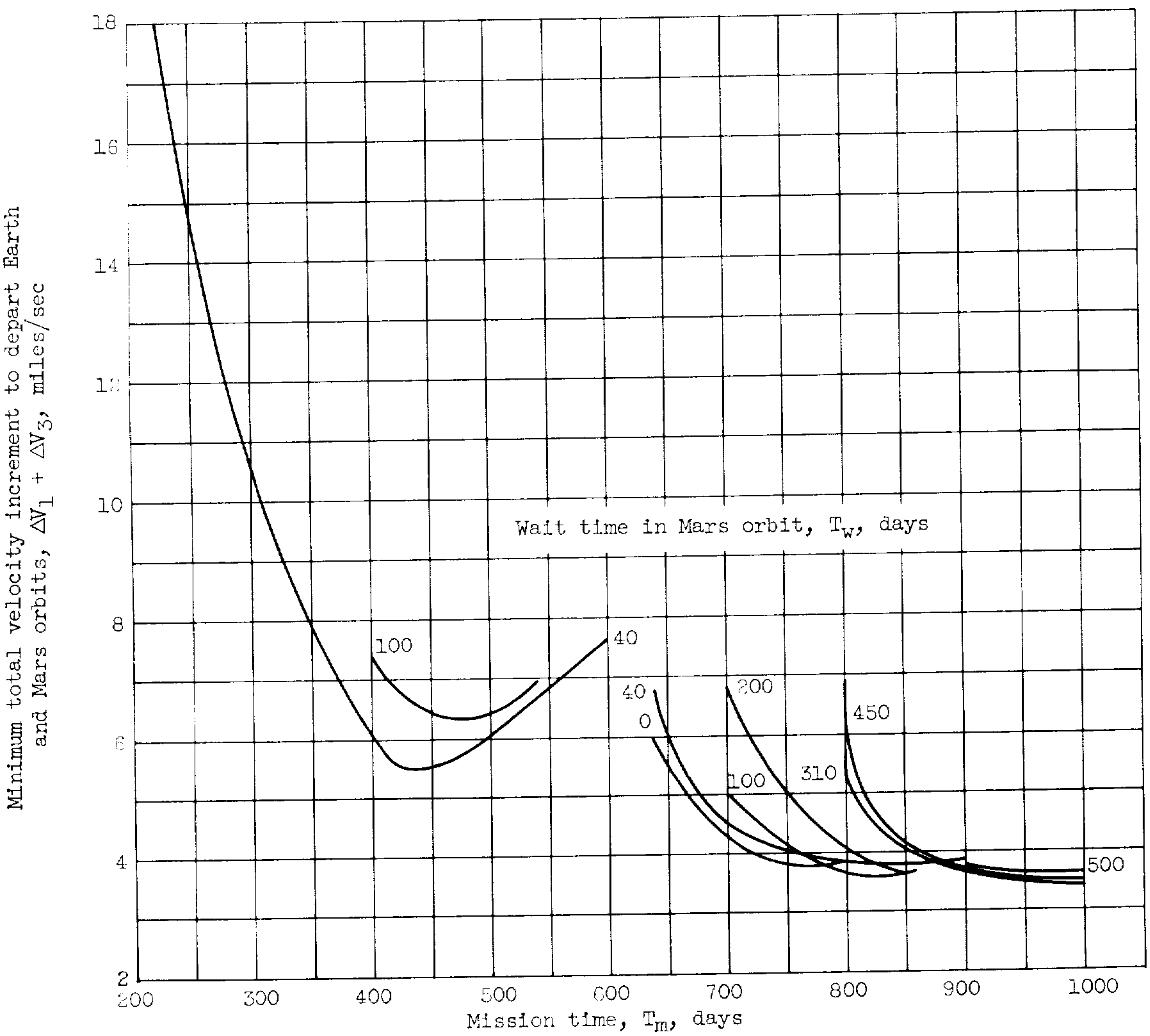
(b) Atmospheric braking at Earth.

Figure 53. - Continued. Minimum total velocity increments required for round trips to Mars. Departure dates, 1970-71.



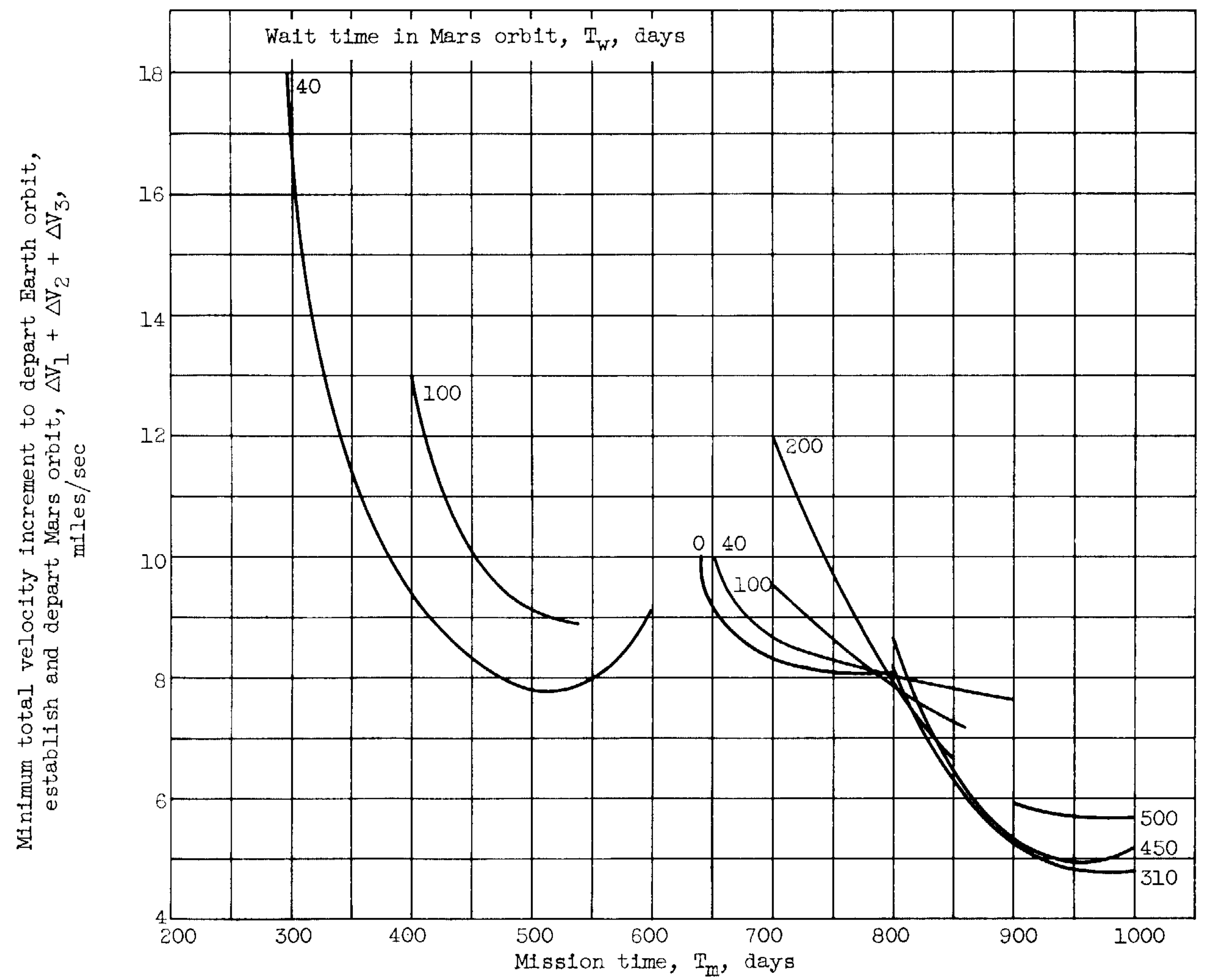
(c) All propulsive braking.

Figure 53. - Concluded. Minimum total velocity increments required for round trips to Mars. Departure dates, 1970-71.



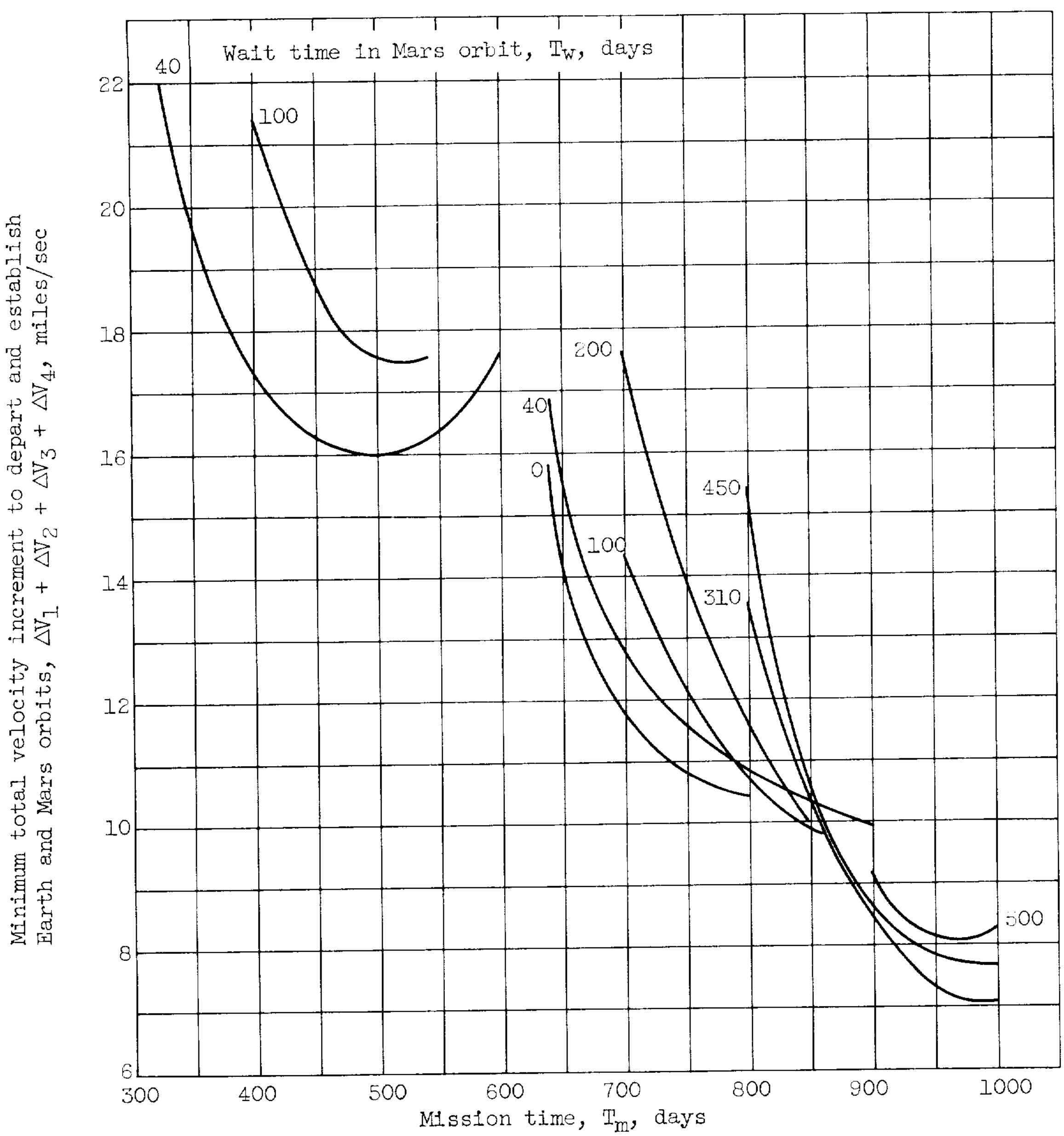
(a) Atmospheric braking at Mars and Earth.

Figure 54. - Minimum total velocity increments required for round trips to Mars. Departure dates, 1978-80.



(b) Atmospheric braking at Earth.

Figure 54. - Continued. Minimum total velocity increments required for round trips to Mars. Departure dates, 1979-80.



(c) All propulsive braking.

Figure 54. - Concluded. Minimum total velocity increments required for round trips to Mars. Departure dates, 1979-80.

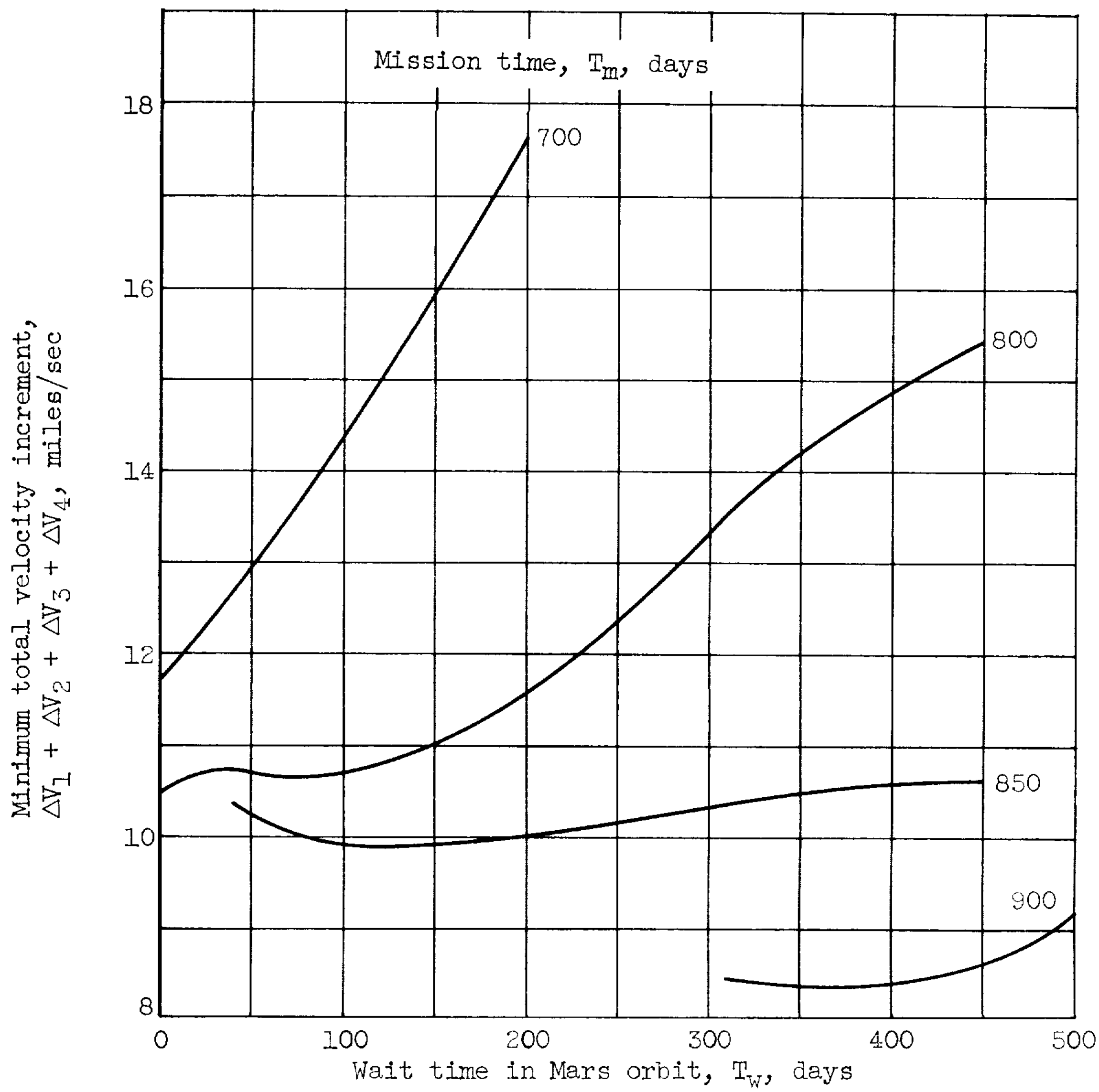
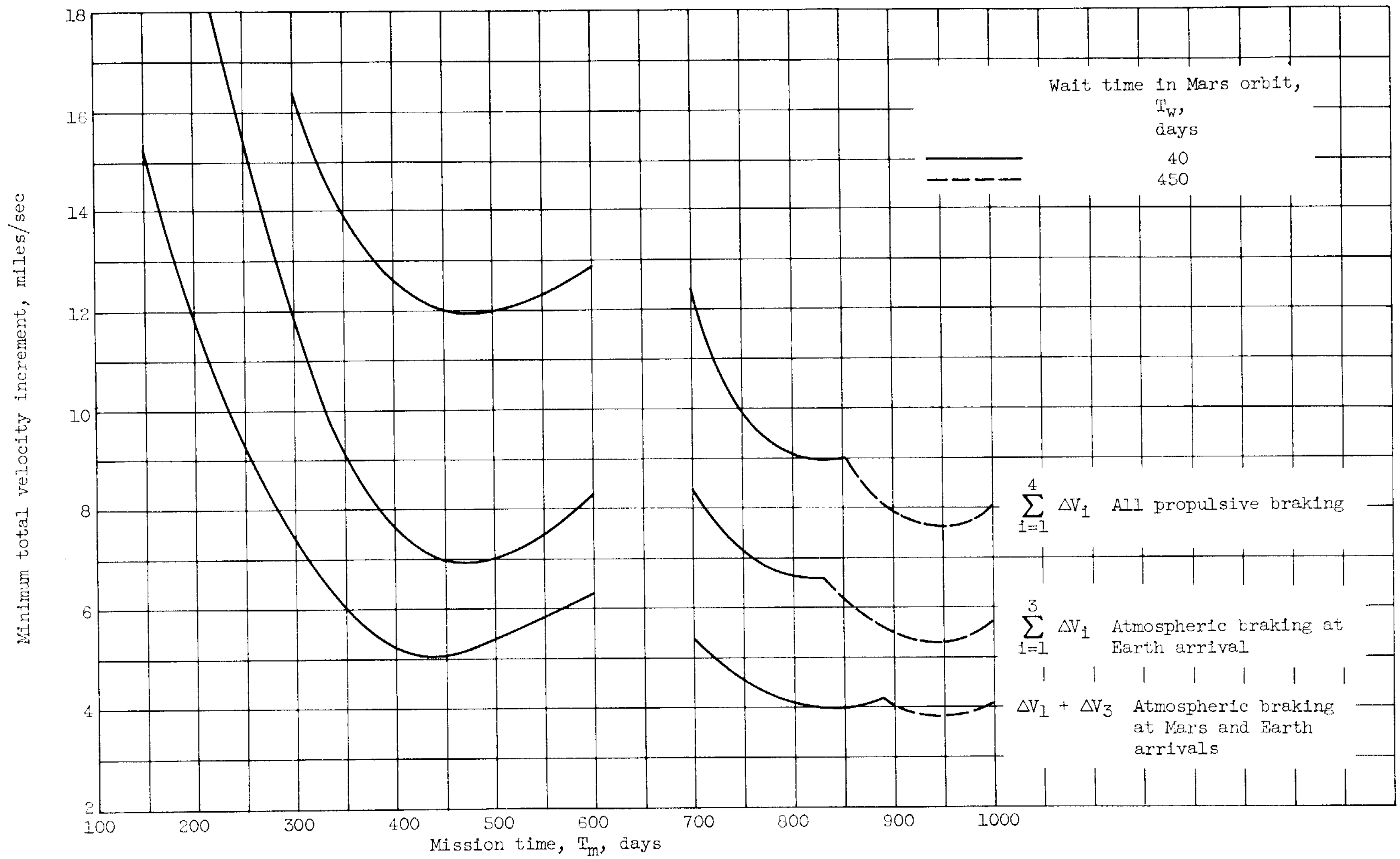
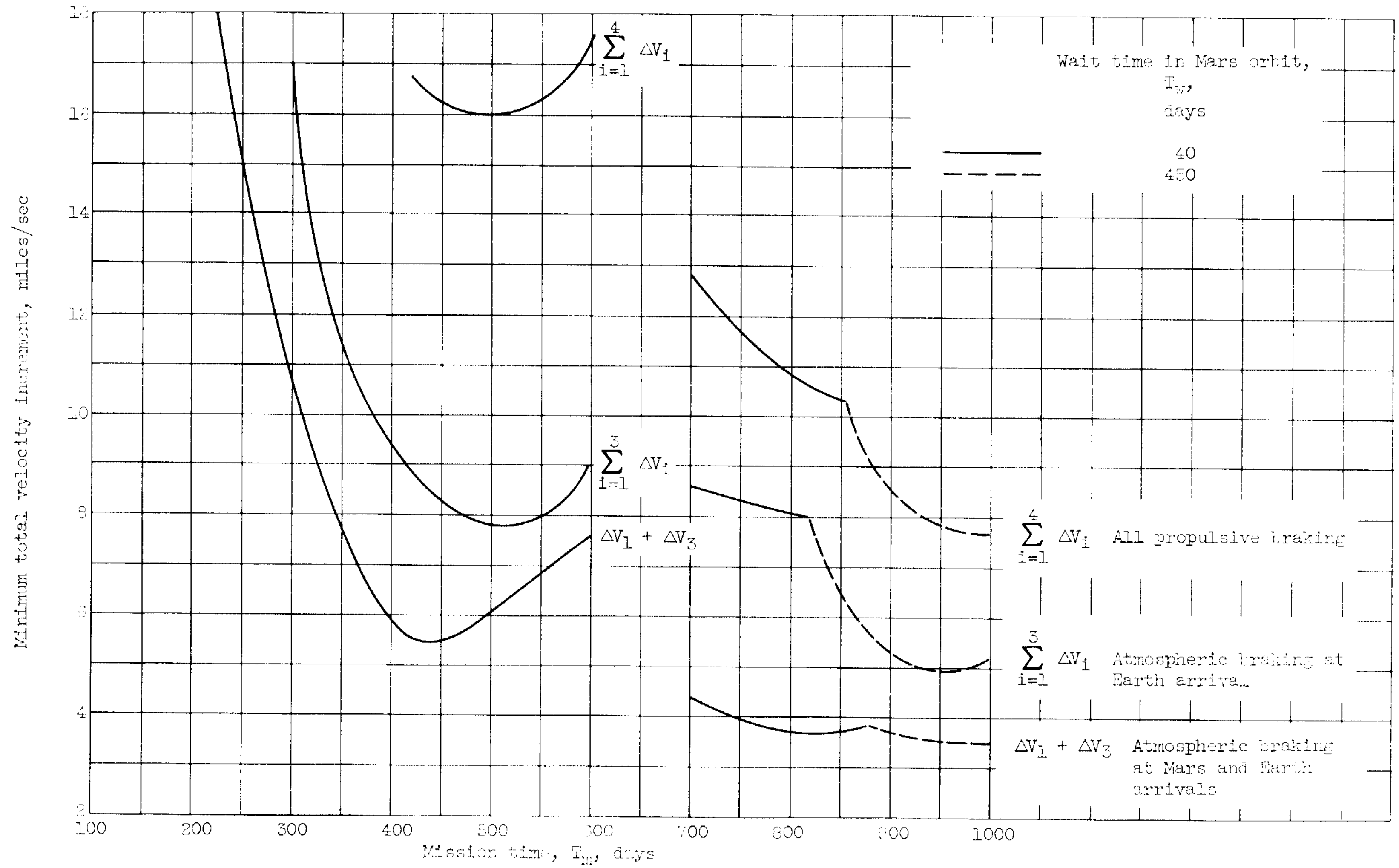


Figure 55. - Effect of wait time on round-trip missions to Mars. Departure dates, 1979-80.



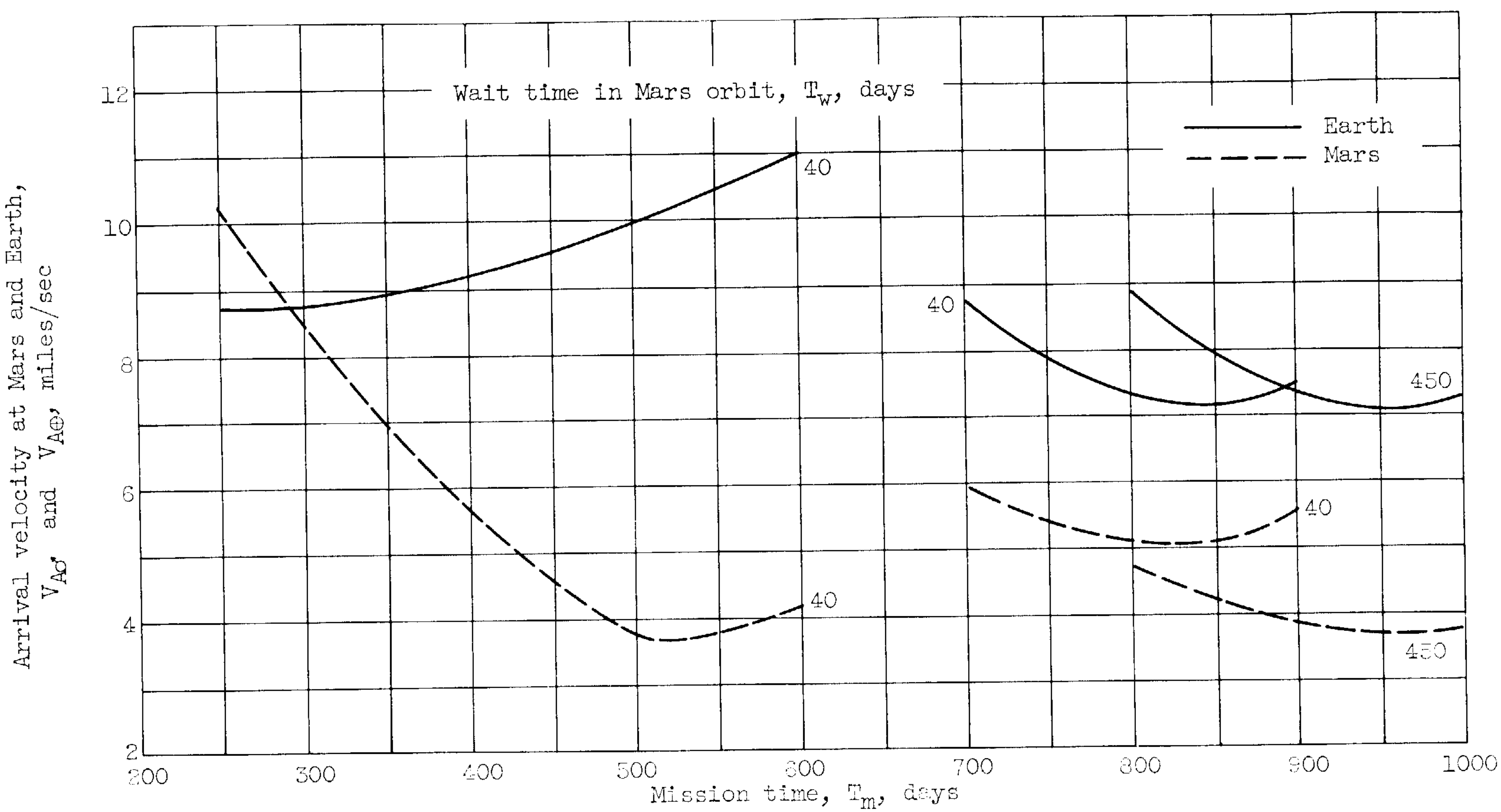
(a) Departure dates, 1970-71.

Figure 36. - Effect of atmospheric braking on total velocity-increment requirements for round-trip missions between Earth and Mars.



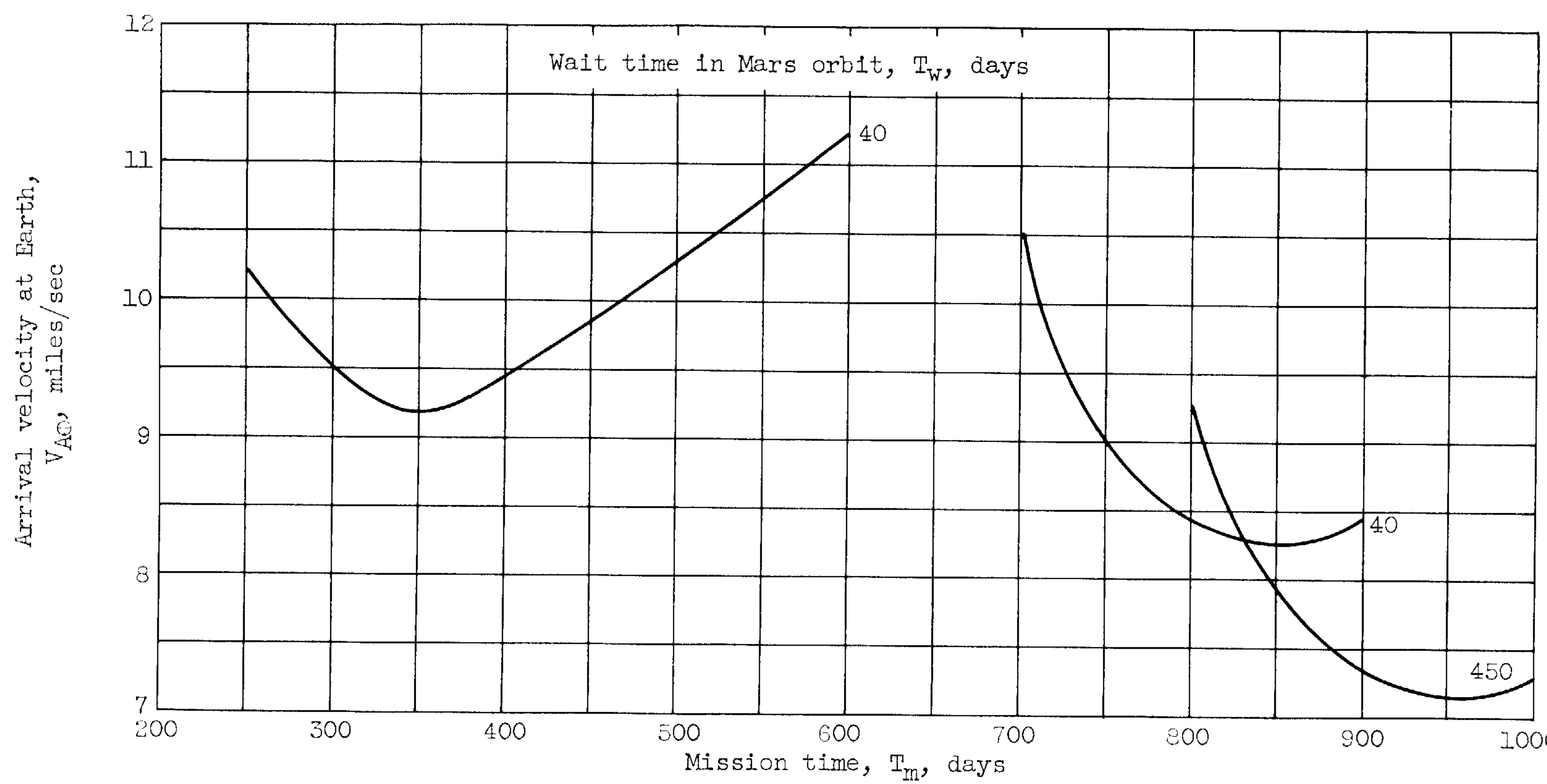
(b) Departure dates, 1979-80.

Figure 58. - Concluded. Effect of atmospheric braking on total velocity-increment requirements for round-trip missions between Earth and Mars.



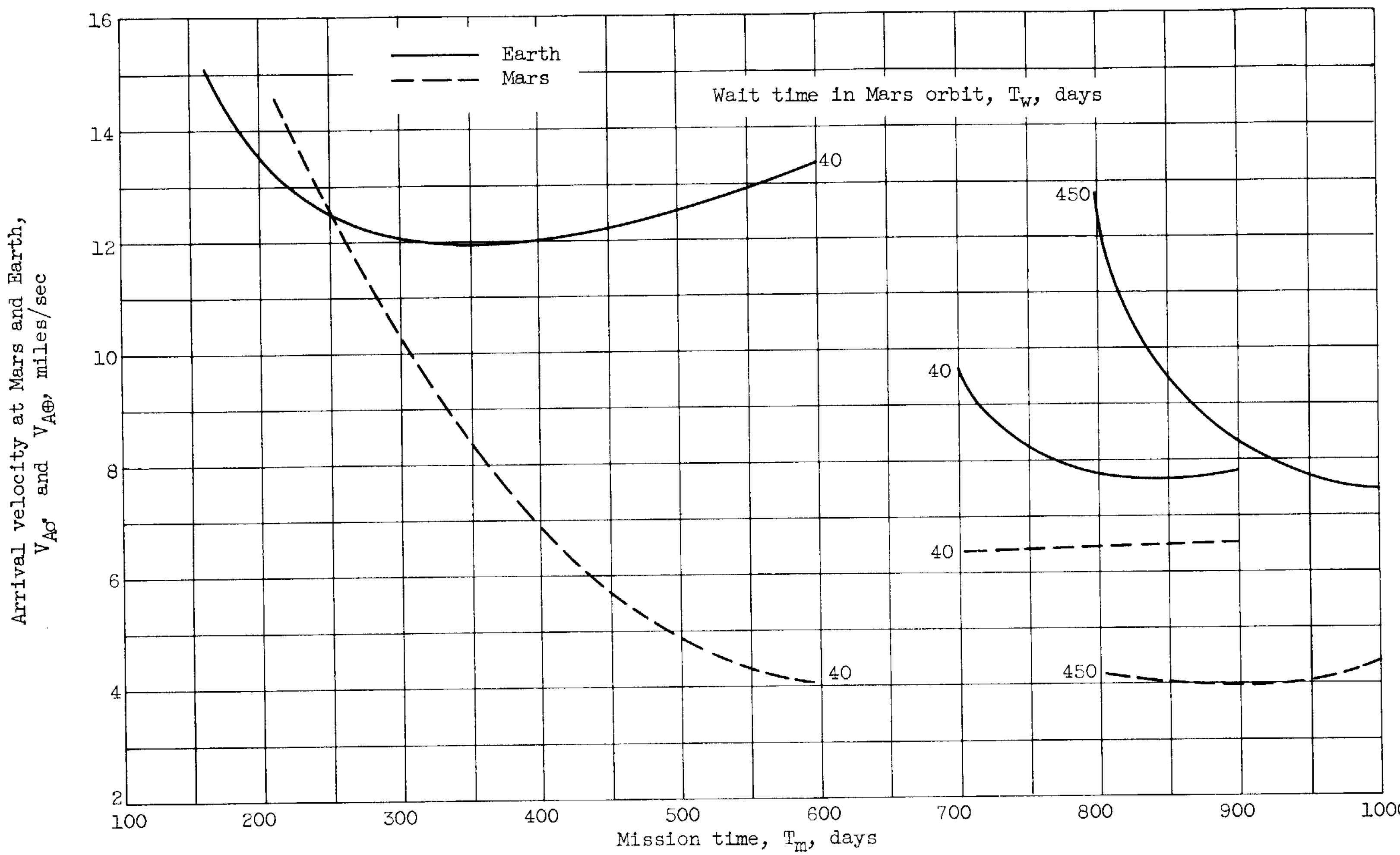
(a) Atmospheric braking at Mars and Earth.

Figure 57. - Arrival velocities for round-trip missions between Earth and Mars. Departure dates, 1970-71. Data for minimum total velocity increment.



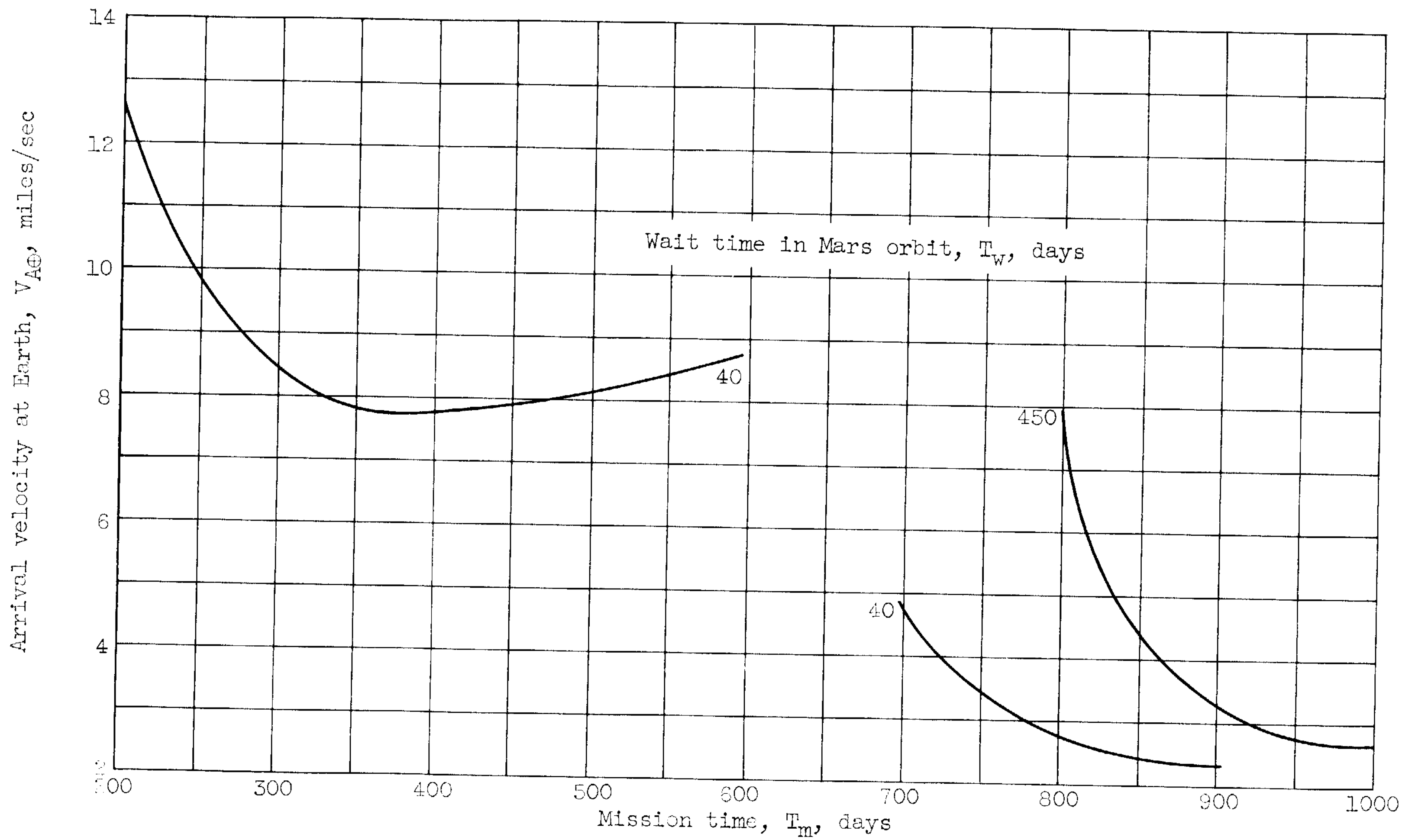
(b) Atmospheric braking at Earth.

Figure 57. - Concluded. Arrival velocities for round-trip missions between Earth and Mars. Departure dates, 1970-71. Data for minimum total velocity increment.



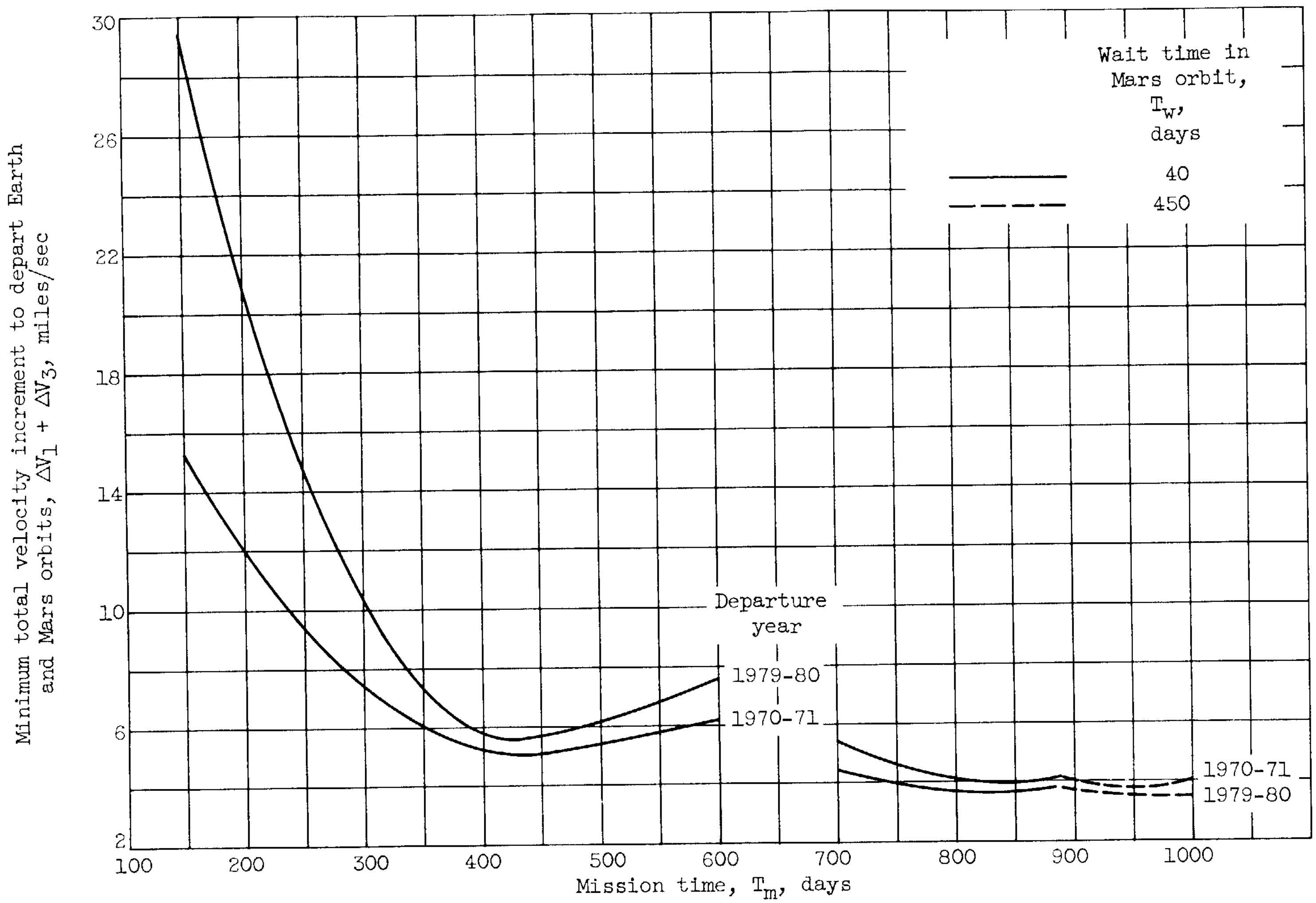
(a) Atmospheric braking at Mars and Earth.

Figure 58. - Arrival velocities for round-trip missions between Earth and Mars. Departure dates, 1979-80. Data for minimum total velocity increment.



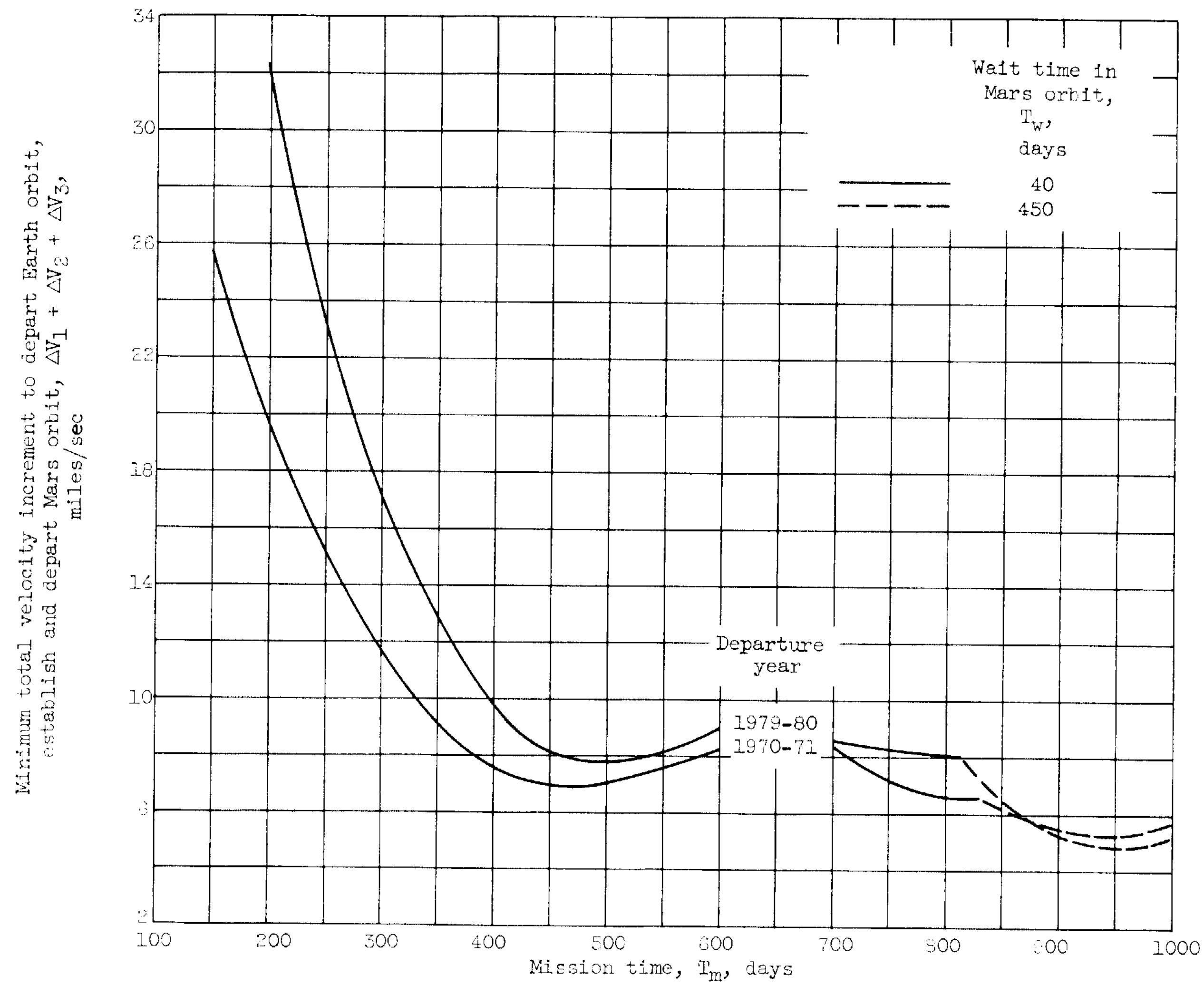
(b) Atmospheric braking at Earth.

Figure 58. - Concluded. Arrival velocities for round-trip missions between Earth and Mars. Departure dates, 1978-80. Data for minimum total velocity increment.



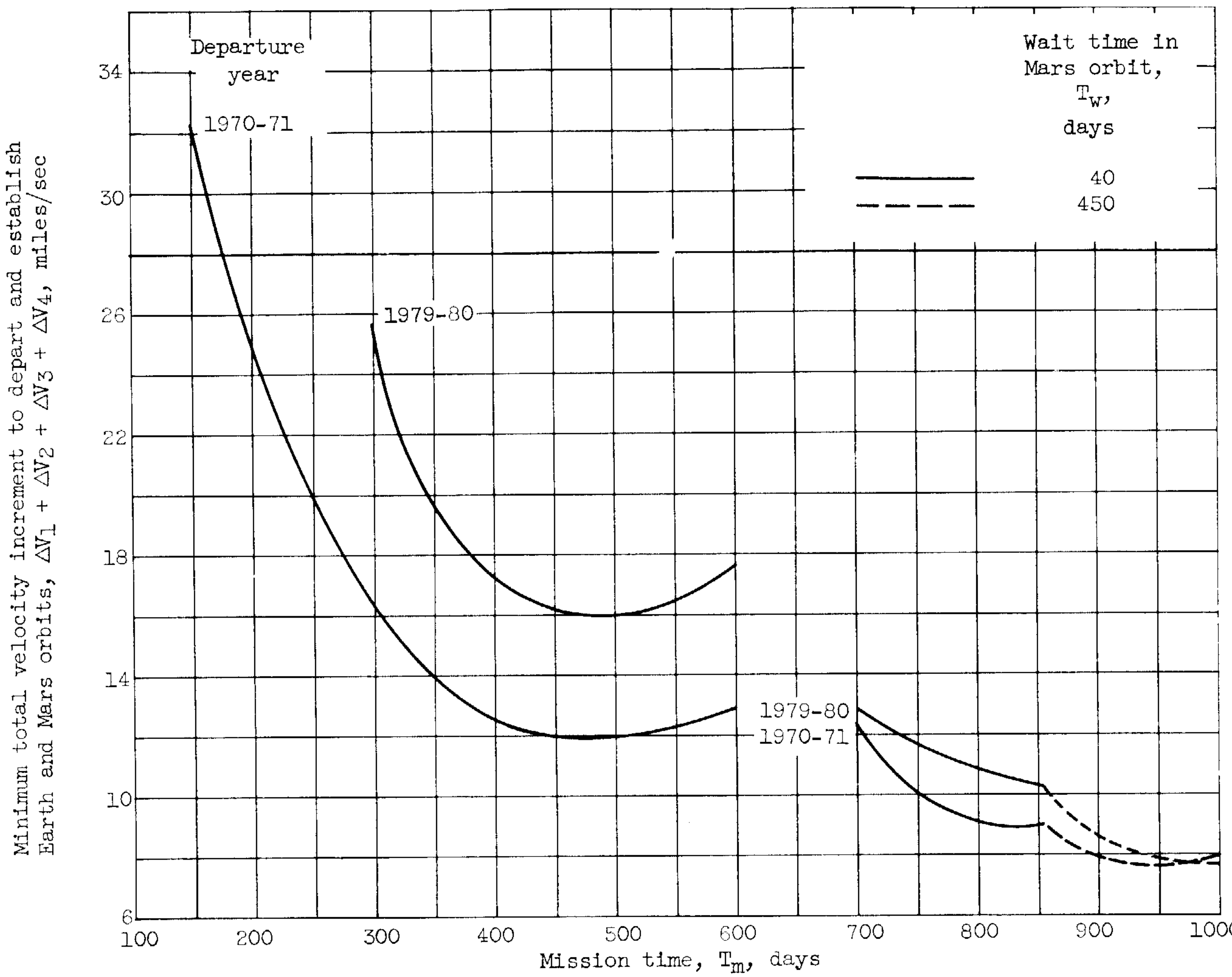
(a) Atmospheric braking at Mars and Earth.

Figure 59. - Effect of synodic period of departure on total velocity-increment requirements for round-trip missions between Earth and Mars.



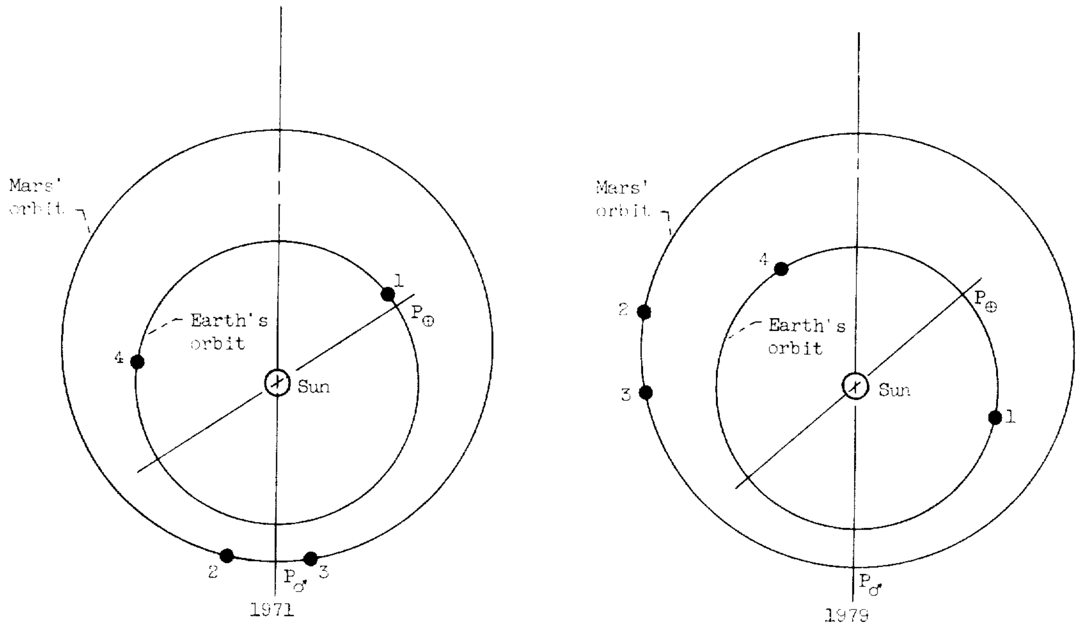
(b) Atmospheric braking at Earth.

Figure 22. - Continued. Effect of synodic period of departure on total velocity-increment requirements for round-trip missions between Earth and Mars.



(c) All propulsive braking.

Figure 59. - Concluded. Effect of synodic period of departure on total velocity-increment requirements for round-trip missions between Earth and Mars.



Trajectory parameter	1971	1979
	Route 1-2	
Heliocentric radius of vehicle at Earth departure, R_1, miles	90.8×10^6	91.95×10^6
Heliocentric radius of vehicle at Mars arrival, R_2, miles	128.43×10^6	144.7×10^6
Heliocentric velocity to depart Earth orbit, V_1, miles/sec	20.1	20.6
Heliocentric velocity on arrival at Mars orbit, V_2, miles/sec	14.1	13.07
Heliocentric path angle of vehicle on Earth departure, α_1, deg	-11.1	0.49
Heliocentric path angle of vehicle on Mars arrival, α_2, deg	8.7	-.002
Velocity of Earth on departure, $V_{\oplus 1}$, miles/sec	18.8	18.7
Velocity of Mars on arrival, $V_{♂2}$, miles/sec	16.41	14.66
Orbit-to-orbit trip time from Earth to Mars, $T_{\oplus ♂}$, days	220	260
	Route 3-4	
Heliocentric radius of vehicle at Mars departure, R_3, miles	128.3×10^6	139.9×10^6
Heliocentric radius of vehicle at Earth arrival, R_4, miles	93.5×10^6	92.7×10^6
Heliocentric velocity to depart Mars orbit, V_3, miles/sec	13.4	10.0
Heliocentric velocity on arrival at Earth orbit, V_4, miles/sec	19.1	18.2
Heliocentric path angle of vehicle on Mars departure, α_3, deg	-7.1	-14.3
Heliocentric path angle of vehicle on Earth arrival, α_4, deg	16.6	36.3
Velocity of Mars on departure, $V_{♂3}$, miles/sec	16.4	15.2
Velocity of Earth on arrival, $V_{\oplus 4}$, miles/sec	18.3	18.5

Figure 60. - Comparison of 500-day round-trip missions to Mars in 1971 and 1979. Wait time in Mars orbit, 40 days. Data for minimum total velocity increment.

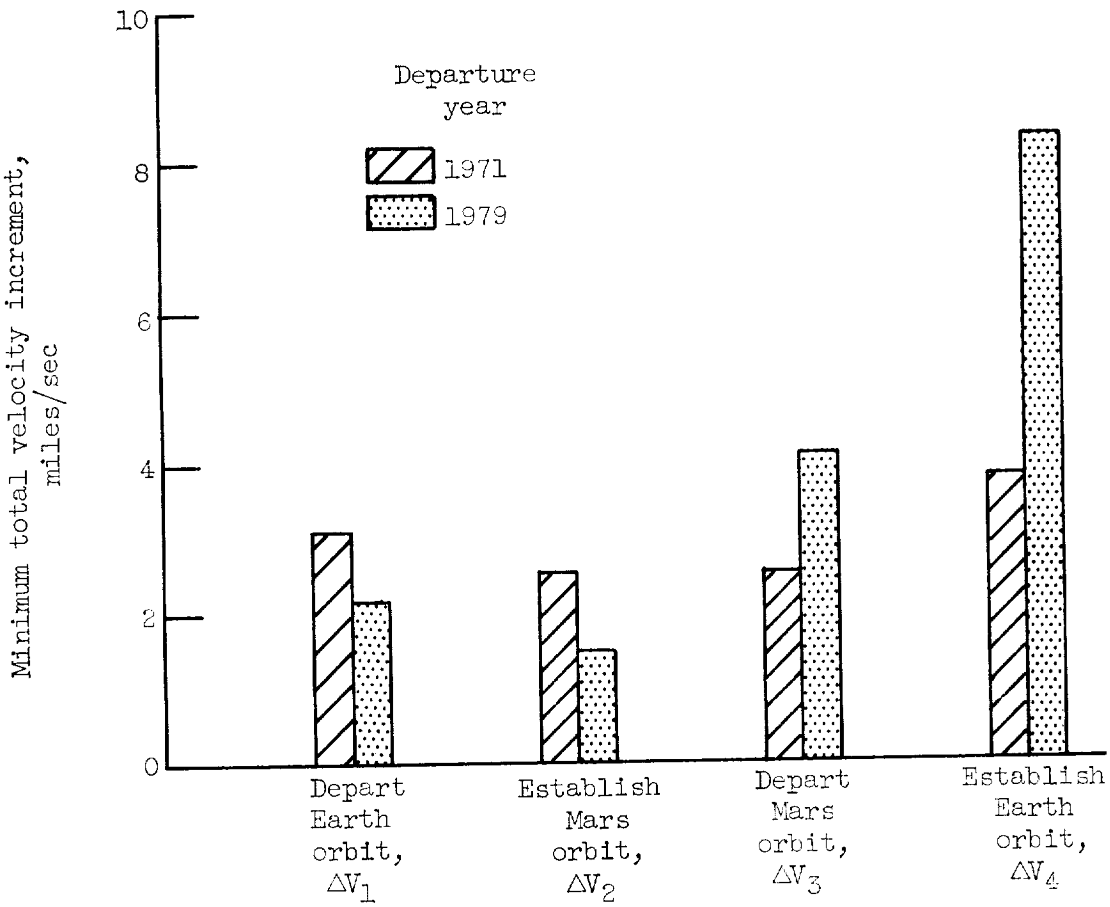
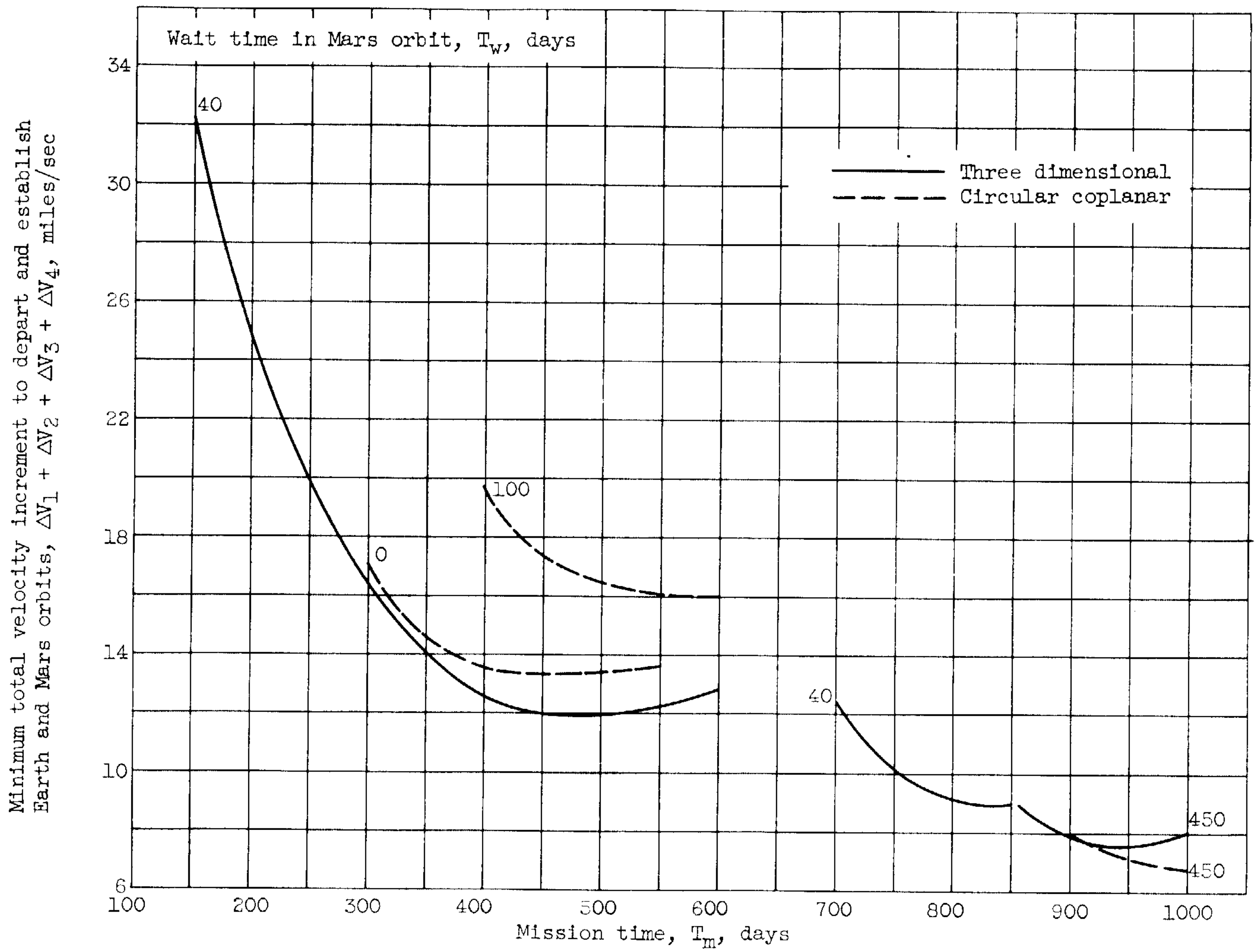
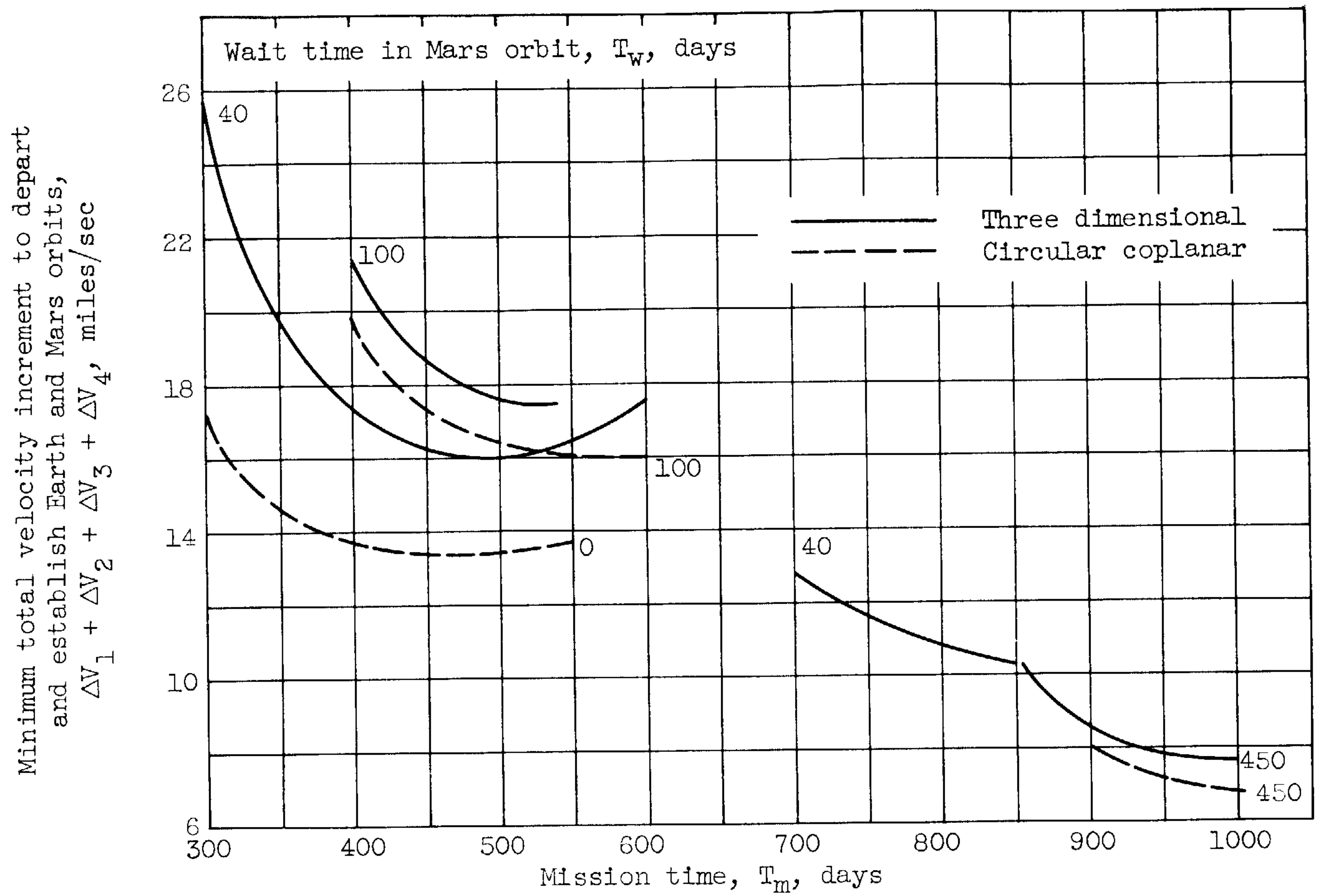


Figure 61. - Effect of synodic period of departure on 500-day round trip to Mars. Wait time in Mars orbit, 40 days.



(a) Departure dates, 1970-71.

Figure 62. - Comparison of circular coplanar and three-dimensional minimum velocity increments for round-trip missions to Mars.



(b) Departure dates, 1979-80.

Figure 62. - Concluded. Comparison of circular coplanar and three-dimensional minimum velocity increments for round-trip missions to Mars.